

You specify by color hex codes qualitative color schemes that pass color deficiency tests

Chatbot

Absolutely! Designing color schemes that are accessible to individuals with color vision deficiencies is essential. Here are some color schemes specified by hex codes that pass color deficiency tests, particularly the deuteranopia (green-blindness) and protanopia (red-blindness).

Color Scheme for Deuteranopia (Green-Blindness):

- #FFA07A (Light Salmon)
- #6495ED (Cornflower Blue)
- #CCCCFF (Periwinkle)
- #FFD700 (Gold)
- #808080 (Gray)

The Process of Colorizing a Data Visualization

1. Establish Data Classes and Key Colors for Visualization.
2. Select Color Rules, Color Harmony per Data Criteria.
3. Build Color Schemes. A Color Suggestion tool might be helpful.
4. Check & Revise for Color Accessibility, Contrast, or Any Post-Processing Conditions.
5. Apply Color Scheme to Data Visualization. Some Modifications might result.

Chatbot Qualitative Color Scheme Applied

Applying Color Theory to Digital Media and Visualization

SECOND EDITION

Theresa-Marie Rhyne



CRC Press
Taylor & Francis Group

Applying Color Theory to Digital Media and Visualization

Applying Color Theory to Digital Media and Visualization provides an overview of the application of color theory concepts to digital media and visualization. It highlights specific color concepts such as color harmony and data color schemes. Examples of generative AI solutions for color scheme suggestion are provided. The usage of these concepts is shown with actual online and mobile tools. Color deficiencies are reviewed, and color tools for examining how a specific color map design will look to someone with the deficiency are discussed. A five-stage colorization process is defined and applied to case study examples.

Features:

- Presents color theory and data color scheme concepts that can be applied to digital media and visualization problems over and over again
- Offers a comprehensive review of the historical progression of color models
- Demonstrates actual case study implementations of color analysis tools
- Provides an overview of color theory and harmony analytics in terms of online and mobile analysis tools
- Teaches the color theory language to use in interacting with color management professionals

Unlike many books on color, which examine artists' use of color, color management, or color science, this book applies fundamental color concepts to digital media and visualization solutions, and the new edition includes generative AI solutions for color suggestion. This is the ideal book for digital media and visualization content creators and developers.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Applying Color Theory to Digital Media and Visualization

Second Edition

Theresa-Marie Rhyne



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

Designed cover image: Theresa-Marie Rhyne

Second edition published 2025

by CRC Press

2385 NW Executive Center Drive, Suite 320, Boca Raton FL 33431

and by CRC Press

4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

CRC Press is an imprint of Taylor & Francis Group, LLC

© 2025 Theresa-Marie Rhyne

[First edition published by CRC Press 2016]

Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, access www.copyright.com or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. For works that are not available on CCC please contact mpkbookspermissions@tandf.co.uk

Trademark notice: Product or corporate names may be trademarks or registered trademarks and are used only for identification and explanation without intent to infringe.

ISBN: 9781032816852 (hbk)

ISBN: 9781032811727 (pbk)

ISBN: 9781003500889 (ebk)

DOI: 10.1201/9781003500889

Typeset in Minion

by codeMantra

*With much love to my parents, Marie Britt Rhyne, M.D.,
and Jimmie Lee Rhyne, M.D., for knowing in their hearts that
I would one day write this book and its 2nd edition.*



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Contents

Acknowledgments 2nd Edition, xiv

Acknowledgments 1st Edition, xvii

Author Biography, xix

INTRODUCTION	1
CHAPTER 1 ■ Introduction to Color Models	4
1.1 THE RGB COLOR MODEL	5
1.2 THE CYAN, MAGENTA, YELLOW, AND KEY BLACK COLOR MODEL	7
1.3 THE RED, YELLOW, AND BLUE “PAINTERS” COLOR MODEL	8
1.4 MOVING BETWEEN COLOR MODELS: COLOR MIXING CHALLENGES	9
1.4.1 When Red and Blue Become Secondary	9
1.4.2 When Blue and Yellow Mix	11
1.5 OVERVIEW OF THE HISTORICAL PROGRESSION OF COLOR	12
1.6 AN EXAMPLE OF COLOR THEORY APPLICATION	16
1.7 PERCEPTUAL LIMITATIONS OF THESE COLOR MODELS REGARDING HUMAN VISION	18
1.8 CONCLUDING REMARKS	18
REFERENCES	19
CHAPTER 2 ■ Review of Color Vision Principles	20
2.1 THE VISIBLE LIGHT SPECTRUM	20
2.2 HUMAN VISION FUNDAMENTALS	21
2.3 TRICHROMATIC COLOR VISION	22
2.4 OPPONENT COLOR THEORY	23
2.5 TRICHROMACY, METAMERISM, AND COLOR CONSTANCY	24
2.6 LUMINOSITY	29

2.7	CHROMATICITY	30
2.8	COLOR VISION DEFICIENCIES	31
2.8.1	Red Cone Color Deficiency	31
2.8.2	Green Cone Color Deficiency	31
2.8.3	Blue Cone Color Deficiency	33
2.8.4	Color Monochromacy and Rod Monochromacy	33
2.9	SIMULATING AND DESIGNING FOR COLOR DEFICIENCIES	34
2.10	AN EXAMPLE OF APPLYING COLOR DEFICIENCY STUDIES	35
2.11	PROBLEMS WITH THE RAINBOW COLOR MAP	35
2.12	CONCLUDING REMARKS	38
	REFERENCES	38
CHAPTER 3	Defining Color Gamut, Color Spaces, and Color Systems	40
3.1	COLOR GAMUT	40
3.2	COLOR SPACES	41
3.3	COMMONLY APPLIED RGB COLOR SPACES	43
3.4	COLORIMETRY	43
3.5	THE CIE XYZ COLOR SPACE AND THE CIE X-Y CHROMATICITY DIAGRAM	45
3.6	CIE LUV AND CIE LAB	49
3.6.1	CIE LUV	49
3.6.2	CIE LAB	50
3.7	COLOR APPEARANCE MODELS	52
3.8	THE MUNSELL COLOR SYSTEM	53
3.8.1	Evolution of the Munsell Color Order System	53
3.8.2	Geometry of the Munsell Color Order System	55
3.8.3	Munsell Color Scales and Digital Media	59
3.9	HUE, SATURATION, AND VALUE (HSV) AND HUE, SATURATION, AND LIGHTNESS (HSL) COLOR SPACES	60
3.9.1	The Challenge of Mixing RGB Lights	60
3.9.2	Historical Development of HSV and HSL Color Spaces	60
3.9.3	The Geometry of HSV and HSL	62
3.9.4	Comparison of HSV and HSL Color Spaces	64
3.9.5	Example of Color Selection Application Using HSV and HSL	66
3.10	HCL AND LIGHTNESS, CHROMA, AND HUE (LCH) COLOR SPACES	67
3.10.1	The Geometry of HCL	68

3.10.2	Perceptual Uniformity and Color Deficiency	68
3.10.3	Oklab and Oklch	70
3.11	WEB COLORS AND HEX TRIPLETS	70
3.11.1	Defining Hex Triplets or Color Hex Codes	70
3.11.2	HTML, CSS, and SVG Web Colors	71
3.11.3	Web Safe Colors	72
3.11.4	An Example of Using Color Hex Codes with a Text-Based Generative AI Tool	73
3.11.5	An Example of Color Capture and Web Color Selection with a Mobile App	74
3.12	PANTONE COLOR MATCHING SYSTEM	75
3.12.1	Evolution of the Pantone Management System	76
3.12.2	Supporting CMYK Color Printing	77
3.12.3	Applying Color Theory Concepts with the Pantone Connect App	77
3.12.4	Color Harmony with Pantone Connect	78
3.13	CONCLUDING REMARKS	78
	REFERENCES	79
CHAPTER 4 ■	Defining Color Harmony	83
4.1	THE COLOR WHEEL	83
4.2	THE STEPS IN CONSTRUCTING A COLOR WHEEL	83
4.2.1	Geometry of the RGB Display Color Wheel	84
4.2.2	Geometry of the CMYK Printers Color Wheel	84
4.2.3	Geometry of the RYB Painters Color Wheel	85
4.2.4	Comparing the RGB, CMYK, and RYB Color Wheels	86
4.3	DEFINING HUES, TINTS, TONES, AND SHADES ON THE COLOR WHEEL	87
4.3.1	Hues	87
4.3.2	Tints	87
4.3.3	Tones	89
4.3.4	Shades	89
4.4	WARM AND COOL COLORS ON COLOR WHEELS	89
4.5	COLOR HARMONY	90
4.5.1	Monochromatic Harmony	91
4.5.2	Analogous Harmony	91
4.5.3	Complementary Harmony	93

4.5.4	Split Complementary Harmony	95
4.5.5	Analogous Complementary Harmony	95
4.5.6	Double Complementary Harmony	98
4.5.7	Tetrad Harmony	100
4.5.8	Diad Harmony	101
4.5.9	Triad Harmony	103
4.6	GAMUT MASKING FOR COLOR HARMONY	105
4.7	REVISITING THE HISTORICAL EVOLUTION OF THE COLOR WHEEL AND COLOR HARMONY	107
4.7.1	Revisiting Isaac Newton's Color Circle	107
4.7.2	Revisiting Moses Harris's Color Wheels	107
4.7.3	Revisiting Johann Wolfgang von Goethe's Color Wheel	107
4.7.4	Examining Phillipp Otto Runge's Color Sphere	108
4.7.5	Revisiting Michel Chevreul's Color Wheel	108
4.7.6	Exploring George Field's Color Wheel	109
4.7.7	Examining Ogden N. Rood's <i>Modern Chromatics</i> Writings	110
4.7.8	Examining Color Wheel Instruction Writings by Louis Prang and Milton Bradley	111
4.7.9	Exploring Bauhaus Contributions to Color Harmony and Interaction	112
4.8	MODERNIZING ALBERS'S INTERACTION OF COLOR STUDIES WITH A WEBSITE	114
4.9	CONCLUDING REMARKS	115
	REFERENCES	115
CHAPTER 5 ■	Translating Between Color Harmony and Data Color Schemes	117
5.1	HISTORICAL EVOLUTION OF DATA COLOR SCHEMES	117
5.2	THE THREE TYPES OF DATA COLOR SCHEMES	118
5.3	THE SEQUENTIAL COLOR SCHEME	118
5.3.1	Single-Hue Sequential Sequences and Monochromatic Color Harmonies	119
5.3.2	Multi-hue Sequential Sequences and Analogous Color Harmonies	119
5.4	THE DIVERGING COLOR SCHEME	119
5.4.1	Diverging Color Schemes and Complementary Color Harmonies	120
5.4.2	Diverging Color Schemes That Are Not Complementary Color Harmonies	122

5.5	THE QUALITATIVE COLOR SCHEME	122
5.5.1	Qualitative Color Schemes and Triad Color Harmonies	124
5.5.2	Qualitative Color Schemes and Square Color Harmonies	124
5.5.3	Color Deficiency Issues for 5-Class Qualitative Schemes and beyond	124
5.6	USING GENERATIVE AI FOR DATA COLOR SCHEMES	126
5.6.1	Generating a Sequential Color Scheme with Adobe Firefly	126
5.6.2	Building a Portfolio of Diverging Color Schemes with ChatGPT	127
5.7	CONCLUDING REMARKS	129
	REFERENCES	130
CHAPTER 6	■ Analyzing and Modifying with Online and Mobile Color Tools	132
6.1	OVERVIEW OF ONLINE AND MOBILE COLOR TOOLS	132
6.2	ADOBE COLOR	133
6.2.1	Creating Color Schemes with the Adobe Color Wheel	134
6.2.2	Capturing a Color Scheme from an Image with Adobe Color	135
6.3	ADOBE CAPTURE	137
6.4	COLOURLOVERS' COMMUNITY	138
6.4.1	Creating a Color Palette with COLOURlovers' COPASO	139
6.4.2	Capturing a Color Palette from an Image with COLOURlovers' COPASO	140
6.5	PALETTON.COM: COLOR SCHEME DESIGNER	141
6.5.1	Left Panel Color Wheel and Color Selection Functions	143
6.5.2	Right Panel Display and Vision Simulation Functions	144
6.5.3	Selecting and Implementing a Square – Tetrad Color Scheme	145
6.6	VIZ PALETTE: A TOOL FOR VIEWING DATA VISUALIZATION EXAMPLES OF COLOR SCHEMES	145
6.7	COLORBREWER 2.0 REVISITED	147
6.7.1	Selecting a Qualitative Color Scheme with ColorBrewer	150
6.7.2	Addressing Photocopy Safe and Printer Friendly Options	151
6.7.3	Using ColorBrewer 2.0 with Only Two Variables	152
6.8	HCL WIZARD	152
6.8.1	Exploring the HCL Wizard Palette Creator Tool	154
6.8.2	Creating an Example with the HCL Wizard Palette Creator	155
6.9	DATA COLOR PICKER	158

6.9.1	Creating a Single-Hue Sequential Color Scheme with Data Color Picker	158
6.9.2	Creating a Diverging Color Scheme with Data Color Picker	158
6.10	CONCLUDING REMARKS	160
	REFERENCES	161
CHAPTER 7	■ Case Study Examples of Colorizing Data Visualizations	162
7.1	MY PROCESS OF COLORIZING A DATA VISUALIZATION	162
7.1.1	Asking ChatGPT for Qualitative Color Scheme Suggestions That Pass Color Deficiency	163
7.1.2	Using Adobe Color to Examine the <i>ChatGPTQualDeuter</i> and <i>ChatGPTQualProtan</i> Suggestions	164
7.1.3	Review of Applying Generative AI (ChatGPT) to Coloring a Five-Element Data Set	165
7.2	USING COLOR DETECTION TO IDENTIFY FRESH COLOR SCHEMES FROM EVERYDAY OBJECTS	166
7.2.1	Being a Color Detective	166
7.2.2	Determining the Color Hex Codes or RGB Numbers	167
7.2.3	Applying the Five-Stage Process of Colorizing a Data Visualization	167
7.2.4	Review of Using Color Detection to Identify Fresh Color Schemes from Everyday Objects	172
7.3	IDENTIFYING PATTERNS ASSOCIATED WITH CORRELATION IN BIOLOGICAL DATA	172
7.3.1	Designing a Color Scheme Solution	173
7.3.2	Review of Results for Identifying Patterns Associated with Correlation in Biological Data	180
7.4	EXPLORING THE IMPACTS OF CLIMATE CHANGE IN TERMS OF THE DEVELOPMENT OF A TROPICAL STORM ANIMATION	180
7.4.1	Building a Color Scheme for the Hurricane Animation Sequence	181
7.4.2	Review of Results for Building a Color Scheme for the Hurricane Animation Sequence	185
7.5	CONCLUDING REMARKS	186
	REFERENCES	186

CHAPTER 8 ■ Review of Basic Concepts Covered	188
8.1 HIGHLIGHTS FROM CHAPTER 1	188
8.2 HIGHLIGHTS FROM CHAPTER 2	190
8.3 HIGHLIGHTS FROM CHAPTER 3	191
8.4 HIGHLIGHTS FROM CHAPTER 4	195
8.5 HIGHLIGHTS FROM CHAPTER 5	196
8.6 HIGHLIGHTS FROM CHAPTER 6	198
8.7 HIGHLIGHTS FROM CHAPTER 7	199
8.8 CONCLUDING REMARKS	200
REFERENCES	201
INDEX, 203	

Acknowledgments 2nd Edition

THE RELEASE OF THE 1st edition of this book changed my life. As a result, I have reprinted the acknowledgments for the 1st edition since so many people provided the foundation for the wonderful life I now have. The book came out in late 2016. From 2017 through 2019, I lectured at conferences and universities on applying color to digital media and visualization. The book became a bestseller among libraries, and I received recognition beyond my dreams. In 2018, I took up ballroom and social dancing to celebrate. My dance efforts did broaden my perspectives, influence my use of color significantly, and contain their own set of adventures. Also in 2018, I joined the Inter-Society Color Council. I attended and presented a poster at their Munsell Centennial Color Symposium. This expanded my color horizons. I went on to write several online discussions on the use of the Munsell color scheme in data visualization for the Munsell Color Company. I treasure the friendships I made with Sandy Sampson and Alessandra White during this period. My courses and tutorials at the annual ACM SIGGRAPH and IEEE Visualization Conferences were well received. SIGGRAPH 2019 was the ultimate experience for me with a standing room only attendance. I thank Barb Helfer and Alex Bryant for their supportive friendship during this period. Also in 2019, Nicholas Polys provided me with a wonderful residency visit at Virginia Tech that moved me into exploring color in virtual reality spaces. After three years, I had gradually transformed into a color maven.

Then, COVID happened in 2020 and the world was altered. Travel, conferences, and university visits came to a halt. However, another unique opportunity presented itself. Elijah Meeks, a founder of the Data Visualization Society and the initial editor-in-chief of their Nightingale journal, suggested that I write short online pieces about my color experiences in data visualization. It was an absolute transforming experience as I became a monthly writer on color. Nightingale published many of my writings, and I formed a lasting friendship with one of its editors, Georges Hattab. In 2021, Georges, Dominik Heider, and I published a paper on *ten simple rules to colorize biological data visualization*. This experience inspired me to develop a *five-stage process for colorizing data visualizations* that I highlight in Chapter 7 of this book. I also began to explore data color schemes and the hue, chroma, and luminance (HCL) model more carefully in these Nightingale writings. Chapter 5 in this 2nd edition reflects my data color scheme explorations. Chapter 3 – Section 3.10 – describes HCL in detail.

In 2021, I also began writing for UX Collective, an independent design publication and blog built to help designers think more critically about their work. In 2022, Fabricio

Teixeira, the editor-in-chief of this Medium publication, championed and increased the distribution of my writings on applying color to data visualization. I continue to write for UX Collective and Nightingale to this day.

By the end of 2022, my world was transformed again. Generative artificial intelligence (AI) had hit the scene with OpenAI's release of ChatGPT. Like most of the world, I began to look at generative AI tools in 2023. While attending a Data Visualization Society online event, one of the panelists said that they were unable to successfully ask generative AI systems to produce data color schemes. My next adventure had presented itself. I was positive I could take on the challenge. My first efforts were with the beta version of Adobe Firefly in June 2023. I am indebted to Jason Forrest of Nightingale for publishing my first writing on this, *The Generative AI Blues: Choosing Data Color Schemes with Adobe's Firefly*, in August 2023. Then, in October 2023, while presenting my IEEE VIS tutorial on color, it was suggested that I consider using color hex codes to ask ChatGPT to suggest data color schemes. We tried some experiments while at IEEE VIS 2023 in Australia, and the concept appeared to have potential and challenges. The training of Open AI ChatGPT, Google Gemini, and Microsoft Copilot as a color suggestion system for data visualization has been the subject of my recent 2024 writings for UX Collective. I am indebted to Fabricio for believing in me once again by publishing these short discussions and to Medium for boosting the distribution of these efforts. My generative AI efforts are part of this 2nd edition. The examples can be found in Chapter 3 – Section 3.11.4; Chapter 5 – Sections 5.6.1 and 5.6.2; and Chapter 7 – Section 7.1.1. Stay tuned for other future adventures in using generative AI for color suggestion.

I thank Elliott Morsia, commissioning editor at CRC Press/Taylor & Francis Group, for the opportunity to prepare this 2nd edition of my book and editorial assistant, Shamayita Dey, who put the first version of this book together for production editing. Additional thanks to Glenon C. Butler Jr, at CRC Press, for production editing as well as Sathya Devi and her team at CodeMantra Publisher Services for finalizing the book. My gratitude to this team is beyond words. As with the 1st edition, Donna Anstey at Yale University Press provided permission to use the various coloring examples I created with the “Interaction of Color by Josef Albers” app in Chapter 4 – Section 4.8. Mark Simpson-Voss returned to coach me on the publishing contract for this 2nd edition. To mention specific family members, Anne Coffey Rhyne has inspired me in the use of color in design, while Carol Rhyne Johnson has continued to encourage me to build my own unique life. My childhood buddies, Jane Clayton and Susan Brown, as well as others from Sanborn Western Camp days, always remind me of my hopes to write on color. My church family, especially the children's ministry, continues to keep me grounded – Nancy and Jessie Holton, Tabitha Perkins, Lindsay Jane Cole, Rebecca Rose White, Evelyn Marks, Phillip Marks, Will Thurman, Danielle Hicks, Ginna Messer, and Peggy Anglin – thank you for making Sundays special. My dance family at the Fred Astaire Dance Studio, especially Serhiy Gennadyovich Titarenko and Aloyna Karachanova, inspire me to keep moving forward not just in dance, but in life each week. Debra and Gary Gibson offer the best place to chill and Carolina Shag dance on Wednesday nights at Loafers Beach Club. Sunday Night Swing Dancing is always a treat with the Carolina Dance Club. The Triangle Swing Dance

Society's monthly swing dances keep me jumping. Lolethia Underdue, known as DL on the 90.7 radio station, and our sharing of jazz music keep me going on weekday afternoons. Most importantly regarding the 2nd edition of this book, thank you Georges Hattab for your devotion to editing and bringing out the best in my early writings for Nightingale and UX Collective – much of this being voluntarily on your part. Finally, I am most thankful for my relationship with God who shares his hope and love for me each day.

Acknowledgments 1st Edition

IT HAS BEEN A lifelong dream of mine to write this book. No dream is ever actualized without the help of many people. Everyone should have an Aunt Mary Bee like I did. She believed in my notions to colorize digital media when the Macintosh computer was very young. My childhood friend, Marleane (Petesy) Owen, joined me on art museum adventures in our youth. This book is dedicated to my parents and I also had the good fortune to have a step-mother, Nancy Vosburgh Rhyne, who promoted my early concepts in K-12 computer graphics education. Judy Brown and Steve Cunningham oversaw my first K-12 computer graphics education grant, through ACM SIGGRAPH.

My 15 years in the Stanford University community, first as a student and later as a staff member in information technology, helped form the foundation for this book. I am indebted to the Palo Alto arts community for championing many of my early computer graphics art shows.

My 13 years as a government contractor with the United States Environmental Protection Agency allowed me to gain fundamental visualization experiences. EPA Project Officer Walter Shackelford championed our founding of the US EPA Scientific Visualization Center. My 8 years at North Carolina State University were equally rewarding. Tom Miller and Mladen Vouk provided terrific opportunities in multimedia and visual analytics. Dan Reed and Alan Blatecky supported my setting up the Renaissance Computing Institute's Engagement Center at North Carolina State University. My collaborators at RENCI@NCSU: Jefferson Heard, Gary Lackmann, John Blondin, Melissa Pasquinelli, and Matt Evans helped me to evolve colorization methods. I am specifically indebted to Steve Chall, Sidharth Thakur and Chris Williams for our many RENCI@NCSU visualization efforts.

Over the last 7 years, Chris Johnson at the Scientific Computing and Imaging Institute at the University of Utah, Kwan Liu Ma at the University of California at Davis, and Pat Hanrahan at Stanford University provided me with consulting opportunities to apply color theory to visualization. Sharon Lin allowed me to coach her on color theory during her PhD studies.

I am most appreciative to Donna Anstey at Yale University Press for providing permission to use the various coloring examples I created with the "Interaction of Color by Josef Albers" app in this book. Rick Adams, Jennifer Ahringer, Sherry Thomas as well as many others with the Taylor & Francis Group helped make publication of this book possible. This book would not have evolved without the terrific online and mobile applications we covered in this book. To all of the software development teams that built these color

applications, thank you very much. I am particularly indebted to my online friends who have shared with me their thoughts about our daily color studies.

In preparing this book, many people encouraged me. I would especially like to thank Marta Fuchs and her brother, Henry Fuchs, who cheered me on as I wrote the book proposal and completed each chapter. Mark Simpson-Voss coached me on publishing contracts and helped me understand fundamentals about book publishing. My cousin, Jane Ann Nelson, continues to champion me online with each color study. Judy Brown and Steve Chall read early versions of various chapters in this book and provided countless edits. Many “creatives” in the Apple Store at the Streets of Southpoint in Durham, North Carolina, taught me illustration techniques that appear in this book. Kim Biese of Papyrus at the Streets of Southpoint let me work for her and explore color schemes in greeting cards. Distant family members Carol Johnson, Billy Johnson, Sally B. Rich, “Aunt” Sarah Williams Britt, and Nanette Lewis Rhyne, endured many conversations about this book. My neighbors, Betty Wilson and Elaine and Melvin Hinton along with Reggie, Wendy, and Victoria Burnette, checked in on me as I prepared content.

The majority of this book was written during my recovery from a set of serious medical conditions. I am indebted to many people at Duke Medical Center for a successful recovery. I would specifically like to thank Michael A. Blazing MD, Anuradha Sabapathi MD, Daniel M. Kaplan MD, Nick Kuntz MD, Edward N. Rampersaud Jr. MD, Andrew D. Petterson MD, John Eppensteiner MD, Marc Samsky MD, and Nilesch Patel, MD. My church family with the Triangle Presbyterian Church kept up their prayers and faith that I would recover. I specifically would like to thank Donna Monzon, Beth Murphy, Rev. Ray Cobb, Rev. Casey Clark, Colleen Loree, Missy Owen, Richard Valenti, Beverly Santos, Jeannie Phelps, Donna Myers, Judy Fleming, Sherene Min MD, Roberta Vandalen, Nancy Holton, Helen Santos, Diane Albert, Andy Batton, Betsy Batton, Julielien Simpson-Voss, Dawn Macelroy, and many others for being there when I genuinely needed it. Finally, I am most thankful for my relationship with God who shares his hope and love for me each day.

Theresa-Marie Rhyne (@tmrhyne), Durham, North Carolina, 2016.

Author Biography

Theresa-Marie Rhyne has over three decades of experience in producing and colorizing digital media and visualization. She has consulted with the Stanford University Visualization Group on a color suggestion prototype system, the Center for Visualization at the University of California at Davis, and the Scientific Computing and Imaging Institute at the University of Utah on applying color theory to ensemble data visualization. Prior to her consulting work, she founded two visualization centers: (1) the US Environmental Protection Agency's Scientific Visualization Center in the 1990s and (2) the Center for Visualization and Analytics at North Carolina State University in the 2000s. Theresa-Marie received a BS degree, two MS degrees, and the Degree of Engineer in Civil Engineering from Stanford University. She entered the computer graphics field as a result of her computational and geographic modeling research in geotechnical and earthquake engineering. She is also an internationally recognized digital media artist who began creating digital media with the early Apple computers, including the colorization of early Macintosh educational software.

In 2020, she began actively writing short articles on applying color theory to data visualization for two online publications: (1) *Nightingale, the Journal of the Data Visualization Society*; and (2) *UX Collective*, an independent design publication and blog built to help designers think more critically about their work. In 2023, she received an IEEE Computer Society Distinguished Contributor Award. She is currently exploring and writing on the use of generative AI for color scheme suggestion.

Her website is www.theresamarierhyne.com. Her writings for Medium and *UX Collective* are listed at <https://medium.com/@theresamarierhyne>. Her writings for *Nightingale, the Journal of the Data Visualization Society*, are listed at <https://nightingaledvs.com/?s=rhyne>. Follow her on X-Twitter at @tmrhyne.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Introduction

COLOR RESULTS FROM OUR eyes' interaction with the light spectrum. For people with eyesight, color is a visual perceptual property of the environment and objects that surround us. Light, regardless of the complexity of its wavelengths, is reduced to three fundamental color components by the human eye. Our retinas contain three types of color receptor cells or cones. These components are long-wavelength or Red cones, medium-wavelength or Green cones, and short-wavelength or Blue cones. Our eyes are wired to understand color in terms of Red, Green, and Blue. However, our brain also gets involved with color perception to make human color vision more intriguing. As a result, when color captured from our eyes travels via the optic nerve to our brain, Red and Green lights mix to become Yellow. This seems unbelievable to us because if we mix Red and Green paints, as we did in kindergarten, we obtain a Gray paint. If we use a color printer, Yellow is one of the inks and no mixing is required to obtain the color. This is because the color models are different in all three cases. The color model for lights or displays is Red, Green, and Blue, while the color model for paint pigments is Red, Yellow, and Blue. The color model for printing with inks is Cyan, Magenta, Yellow, and Key Black. Additionally, the appearance of a color changes according to its context and is influenced by the other hues and lighting surrounding it. Working with color is complicated and not always intuitive.

A body of knowledge, called color theory, has evolved over the centuries to provide guidance in visual effects and mixing of color combinations. These color management challenges are just some of the many components we present in this book on *Applying Color Theory to Digital Media and Visualization*. We demonstrate how the inter-relationships of color principles influence the process of creating color schemes for digital media and visualization. We discuss visual simulation tools that indicate how individuals with color deficiencies might view specific color images or palettes. Working with online and mobile color evaluation tools, we show how to analyze a color scheme from an existing digital image and save it for future application.

Using the color wheel representation and organization, we define the fundamentals of color harmony and highlight how to use these concepts in visual content creation. We also introduce data color schemes that are used in the data analytics and visualization

Visual summary: Applying color theory to digital media and visualization



FIGURE 1.1 Visual summary of highlights from *Applying Color Theory to Digital Media and Visualization*, 2nd Edition. Illustration by Theresa-Marie Rhyne, 2024.

communities. We show how to translate between these two concepts. We provide a five-stage process for colorizing data visualizations and apply it to several case studies. We describe existing color applications and use generative artificial intelligence (generative AI) for color suggestion. Practical tools and methodologies are demonstrated for you to use in your own efforts to create digital media and visualizations. Figure I.1 shows a visual overview of the concepts covered in our discussions.

In this book, we have capitalized colors. As an example, rather than writing “yellow”, we write “Yellow” to note the importance of colors and hues in our discussions. We also provide many references for further reading on topics. We note URLs to access an online tool or find information about acquiring a particular color app. In Chapter 8, we provide both a text summary and a visual collage of selected illustrations for each prior chapter in the book.

We use the color tools and techniques presented in these chapters on a daily basis. Every day, I enjoy exploring a new aspect of color theory and actively belong to social media sites for sharing color work. Relationships with colleagues at Adobe Color’s social media site, the COLOURlovers online creative community, the Data Visualization Society’s Slack community, and Medium’s website, as well as comments from X-Twitter, LinkedIn, Instagram, and Facebook postings, were very helpful in developing several of the concepts presented here. So, let’s get started on our journey of color exploration.

Introduction to Color Models

A *COLOR MODEL* IS A structured system for creating a full range of colors from a small set of defined primary colors. There are three fundamental models of color theory. As shown in Figure 1.1, these are as follows: (1) the Red, Green, and Blue (RGB) color model of lights and display originally explored by Isaac Newton in 1666; (2) the Cyan, Magenta, Yellow, and Key Black (CMYK) model for printing in color originally patented by Jacob Christoph Le Blon in 1719; and (3) the Red, Yellow, and Blue (RYB) painters model fully summarized by Johann Wolfgang von Goethe in 1810. Figure 1.1 provides a visual summary of these three fundamental models of color theory.

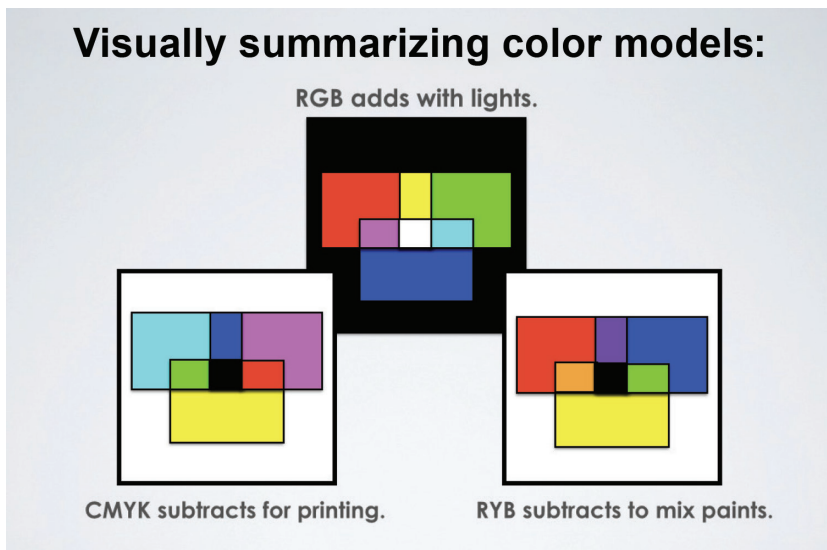


FIGURE 1.1 Visual summary of color models. The Red, Green, and Blue (RGB) color model is an additive color model for displays. The Cyan, Magenta, Yellow, and Key Black (CMYK) color model is a subtractive color model for printing. The Red, Yellow, and Blue (RYB) color model is designed for mixing colors with paints. Source: images created by Theresa-Marie Rhyne, 2016.

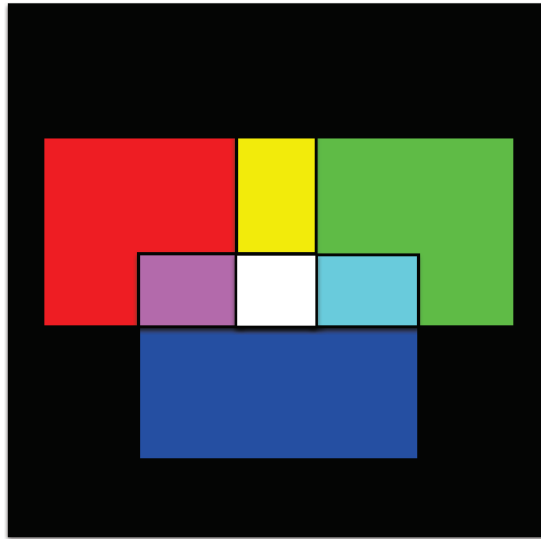


FIGURE 1.2 Illustration of the Red, Green, and Blue (RGB) color model. Source: image created by Theresa-Marie Rhyne, 2016.

1.1 THE RGB COLOR MODEL

As shown in Figure 1.2, the RGB color model assembles the primary lights of Red, Green, and Blue together in various combinations to produce a broad range of colors. The Red light and Green light when combined together produce the Yellow light. The RGB color model is termed an additive color model where the combination of the RGB primary lights together produces the White light. The RGB color model is used in many color image-producing technologies that include conventional photography and the display of images in electronic systems. Examples of RGB input devices are image scanners, video games, digital cameras, and television and video cameras. RGB output devices encompass the broad range of television set technologies and video projector systems, along with computer and mobile phone displays. The RGB color model has a solid grounding behind it in regard to physics and the human perception of colors. We provide a historical overview of this grounding below.

In 1666, Isaac Newton explored the dispersion of White sunlight into a rainbow of colors. His experiments involved holding a prism of glass in the path of rays of sunlight coming through a hole in a darkened room. The White light split into Red, Orange, Yellow, Green, Blue (actually Cyan), Indigo (frequently referred to as Dark Blue), and Violet. Newton asserted that different colors combined to produce a White light. Newton published his findings in a book entitled *Opticks* in English in 1704 [1]. Newton's rainbow color map for light has become a fundamental approach in the design of today's visualization and digital media presentations. Newton also developed the initial concept of the color wheel that we will highlight later in this chapter on color models. Although Newton did not define RGB as primary colors, his research was the first step in showing that color lights combined together to produce a broad array of additional colors. In Figure 1.3a, we diagram the conventional arrangement of what Newton defined as the dispersion

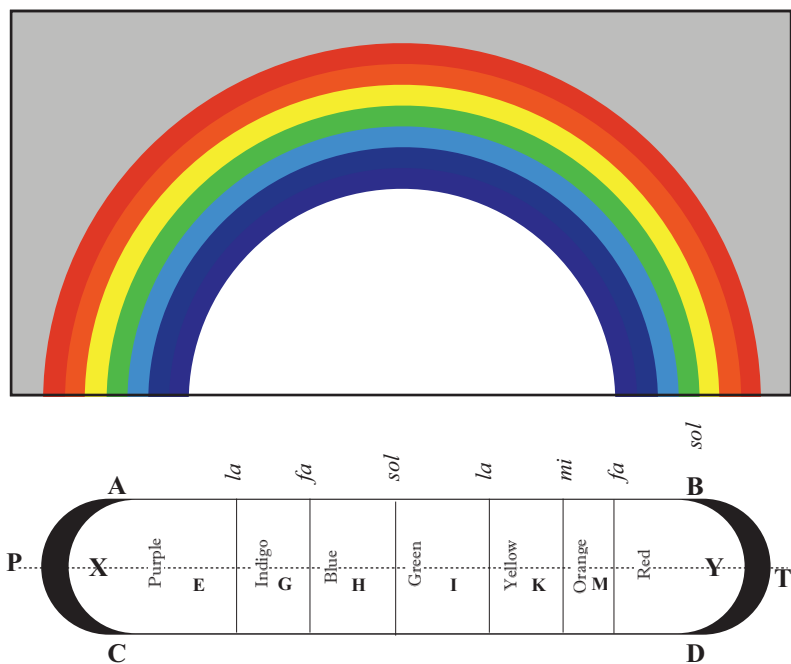


FIGURE 1.3 Top image: rainbow diagram showing the conventional arrangement of colors (Red, Orange, Yellow, Green, Blue (actually Cyan), Indigo (Dark Blue), and Violet) based on Isaac Newton’s writings [1]. Image created by Theresa-Marie Rhyne, 2016. Bottom image: redrawing of Isaac Newton’s diagram of the spectrum of light. Adapted from Reference [1]. Image created by Theresa-Marie Rhyne, 2016.

of White light into a rainbow of colors. In Figure 1.3b, we show an adapted version of Newton’s original drawing of the spectrum of colors from his 1704 *Opticks* book. Newton’s notations in the diagram refer to an analogy he developed where the seven colors of the rainbow correspond to the musical concept that an octave displays seven sound intervals.

The RGB color model was actually defined in regard to the theory of trichromatic color vision. In 1802, Thomas Young, in a lecture entitled “On the Theory of Light and Colours”, postulated that each human eye had three types of photoreceptors (referred to today as cone cells). Young further proposed that each photoreceptor is sensitive to specific ranges of the visible light. In 1851, Herman von Helmholtz, in his *Treatise on Physiological Optics*, added to the theory further by noting that the three types of cone photoreceptors are long preferring (Red), medium preferring (Green), and short preferring (Blue). We will highlight these color vision concepts further in Chapter 2 of this book.

In 1861, during a lecture on his color studies at the Royal Institute in the United Kingdom, James Clerk Maxwell provided the first widely recognized demonstration of the RGB color model, as well as what is often called the first color photograph [2]. In his lecture, Maxwell showed an image of a tartan ribbon photographed by a professional photographer on three plates through Red, Green, and Blue-Violet filters respectively. Combining these filtered images together onto a screen produced a reasonable color display of the tartan ribbon.

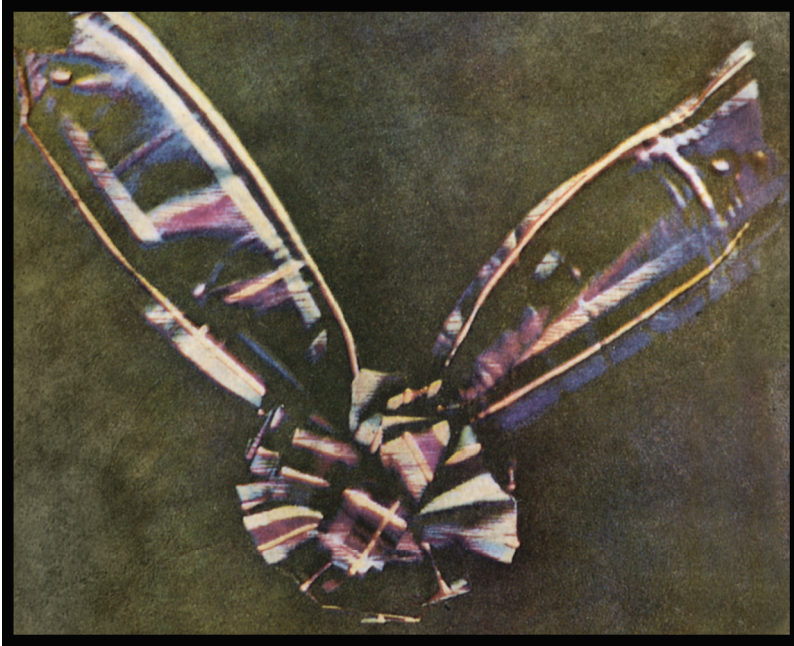


FIGURE 1.4 Image of a tartan ribbon that James Clerk Maxwell demonstrated in his 1861 lecture on the Red, Green, and Blue (RGB) color model. This image is also considered the “first color photograph” [2]. Public domain.

Maxwell’s demonstration, shown in Figure 1.4, although revolutionary in 1861, is now in modern use in video projection systems and is fundamental in regard to television, video, computer, and mobile phone displays.

1.2 THE CYAN, MAGENTA, YELLOW, AND KEY BLACK COLOR MODEL

The Cyan, Magenta, Yellow, and Key Black (CMYK) color model is designed to support color printing on a White paper. The CMYK color model is termed a subtractive color model where the starting point begins with a White or light surface. Color pigments reduce the reflection of the original White light. The color inks thus “subtract” from the original White surface. Typical output devices for the CMYK color model include color inkjet, laser, and dye-sublimation printers. Each device has its own particular technology for color image reproduction. In Figure 1.5, we illustrate the CMYK color model.

Historically, for color printing processes to work, individual plates were created for the Cyan, Magenta, and Yellow (CMY) color pigments. The plates were registered over top of each other to produce full color images, and the process was called a three-color printing process. When the primary pigments of Cyan, Magenta, and Yellow were combined together as inks, in equally large amounts, the result was a Black color. When color printing was put into practice, combining the CMY inks together became an expensive process, and in some situations, certain papers were unable to absorb all of the ink required. As a result, the color printing process was modified to allow for a Black plate to support the printing of the Black text and other Black elements with the Cyan, Magenta, and Yellow

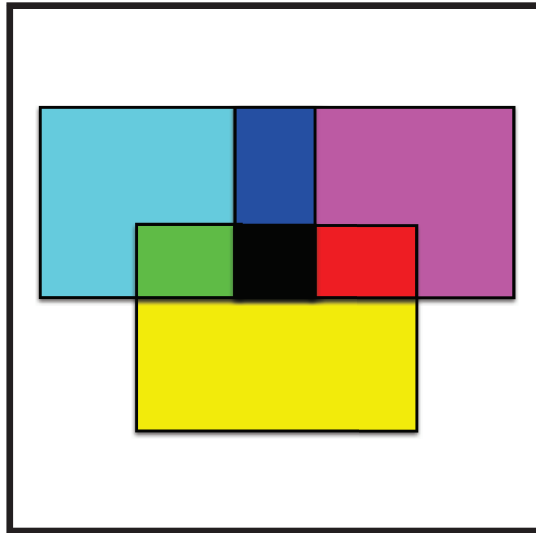


FIGURE 1.5 Illustration of the Cyan, Magenta, Yellow, and Key Black (CMYK) color model. Image created by Theresa-Marie Rhyne, 2016.

printing plates being registered or “keyed” against the Black plate. This color printing process and its associated model was thus termed the Cyan, Magenta, Yellow, and Key Black (CMYK) color model. CMYK is thus a four-color printing process.

Today, when a digital image is printed, the RGB numeric values of the image are converted to the CMYK numeric values of a printer. In theory, the RGB and CMYK color models are complementary to each other. Various combinations of the RGB primaries of the RGB color model produce Cyan, Magenta, and Yellow. The reverse is true for the Cyan, Magenta, and Yellow primaries where combinations of the CMYK color model produce RGB. In practice, these combinations are not purely complementary since the RGB color model involves lights and the CMYK color model involves pigments. Colors selected and matched on an RGB mobile phone can appear with different intensities, perhaps even more subdued, when reproduced on a White paper via a CMYK inkjet printer. In Figure 1.6, we diagram the complementary relationship between the RGB and the CMYK color models.

Three-color and four-color reproduction processes were first patented in 1719 by Jacob Christoph Le Blon. Le Blon actually used RYB inks on individual metal plates with a Key Black registration plate as the foundation for his color reproduction methods. Like the CMYK color model, the RYB color model is also a subtractive model. We will highlight the RYB painters color model in the next section of this chapter.

1.3 THE RED, YELLOW, AND BLUE “PAINTERS” COLOR MODEL

The RYB color model is a subtractive color model for mixing painting pigments. It is usually the first color model we learn at an early age, perhaps in kindergarten. Starting with a White paper, the RYB color pigments when combined together yield Black as with the CMYK color model. Secondary colors that result from mixing primary pigments include (1) the combination of Red and Yellow to yield Orange; (2) the combination of Yellow and

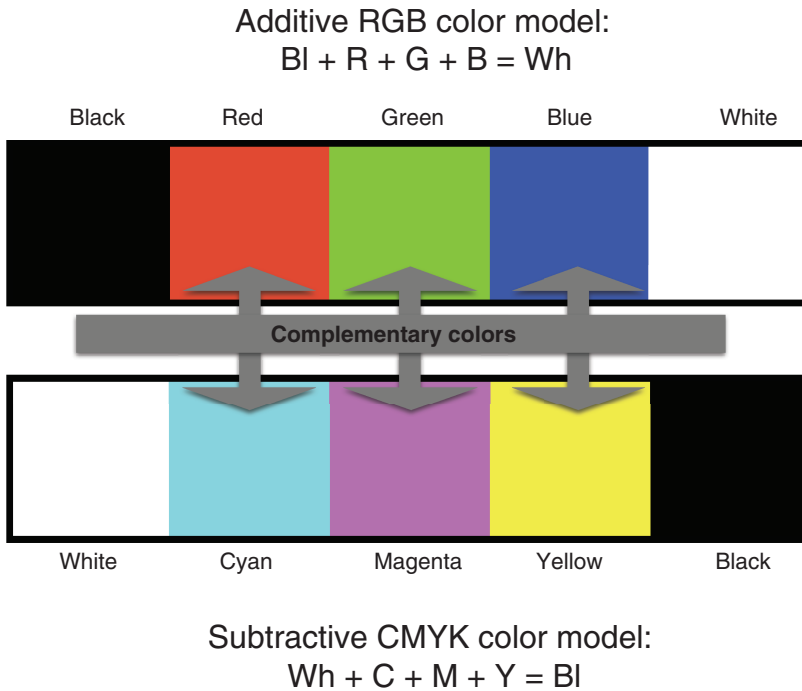


FIGURE 1.6 Diagram of the complementary relationship between the Red, Green, and Blue (RGB) color model and the Cyan, Magenta, Yellow, and Key Black (CMYK) color model. Notice that with RGB, we begin with Black (BL) and then add Red (R), Green (G), and Blue (B) colors to yield a White (Wh) light. With CMYK, we begin with a White (Wh) surface and then combine Cyan (C), Magenta (M), and Yellow (Y) pigments to yield a Black (Bl) ink. Image created by Theresa-Marie Rhyne, 2016.

Blue to yield Green; and (3) the combination of Blue and Red to yield Purple. The RYB color model is used in art and art education. In Figure 1.7, we illustrate the RYB color model.

1.4 MOVING BETWEEN COLOR MODELS: COLOR MIXING CHALLENGES

The process of moving between these color models is far from simple and results in mysterious discoveries about mixing colors. Let's consider two here: (1) Red and Blue become secondary colors in the CMYK color model; and (2) combining Blue and Yellow produces different results depending on whether it is the RGB or RYB color model.

1.4.1 When Red and Blue Become Secondary

Color combinations created by the equal mixture of two primary colors are called secondary colors. Usually, we think of Red as a primary color with the RGB and the RYB color models. Rarely do we realize that Red is a secondary color in the CMYK color model. During the color printing process, Red is produced by combining Yellow and Magenta. A similar situation exists for Blue. Blue is also a secondary color in the CMYK color model. Cyan and Magenta combine to produce Blue during the color printing process. Figure 1.8 illustrates these color mixing concepts. These can become

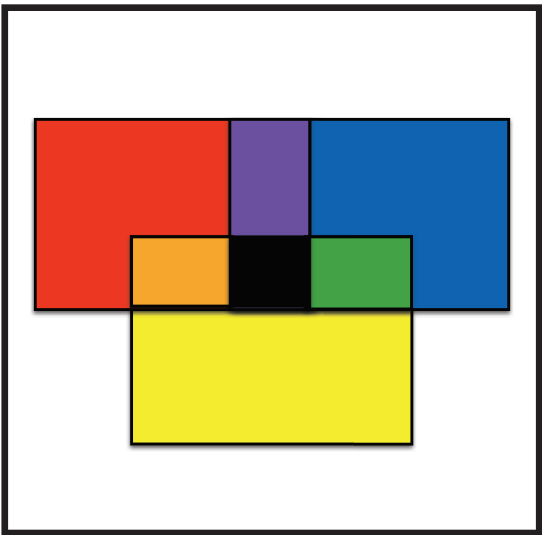


FIGURE 1.7 Illustration of the Red, Yellow, and Blue (RYB) color model. Image created by Theresa-Marie Rhyne, 2016.

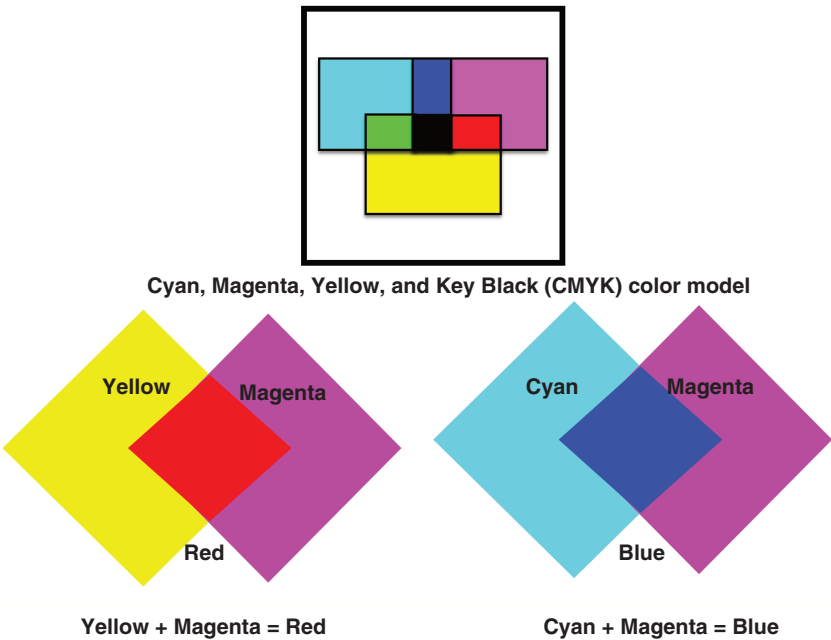


FIGURE 1.8 Illustration of how equal amounts of Yellow combined with Magenta equal Red and equal amounts of Cyan combined with Magenta equal Blue in the Cyan, Magenta, Yellow, and Key Black (CMYK) color model. Image created by Theresa-Marie Rhyne, 2024.

important considerations when moving a digital image that includes a significant amount of Red and/or Blue from a computer display to a printed copy. We will discuss these types of issues in future chapters of this book.

1.4.2 When Blue and Yellow Mix

Very often, the combination of Blue and Yellow suggests Green. Many of us recall mixing Blue and Yellow paints to achieve this result based on the RYB color model. Here, the primary colors are RYB. Green is the secondary color from combining Blue and Yellow. However, for the RGB color model, the results are very different. The display model is based on color lights where the primary colors are RGB. With color lights, the Red and Green primary lights combine to produce a Yellow secondary light. Combining Blue and Yellow lights in this display color space produces a White light. The RGB color model is fundamental for color in digital media compositions. Figure 1.9 illustrates the differences between mixing Blue and Yellow with paints in the RYB color model and mixing Blue and Yellow with lights in the RGB color model.

These and other challenges of moving between color models have existed for centuries. As discussed previously, Newton published his rainbow color map findings in 1704. In that time period, color image production and reproduction were performed with paint pigments on a White or Cream canvas. Painters relied upon the RYB color model for mixing and understanding colors. The theory of trichromatic (RGB) color vision had not been postulated. Although mirror displays existed, photographic, television, video, computer, and mobile display technologies with RGB lights had not been developed. In the 18th century, the RYB color model was the foundation of theories of color vision.

As a result, it was difficult for painters to understand how to incorporate Newton's dispersion of White sunlight into a rainbow of colors observations into their working

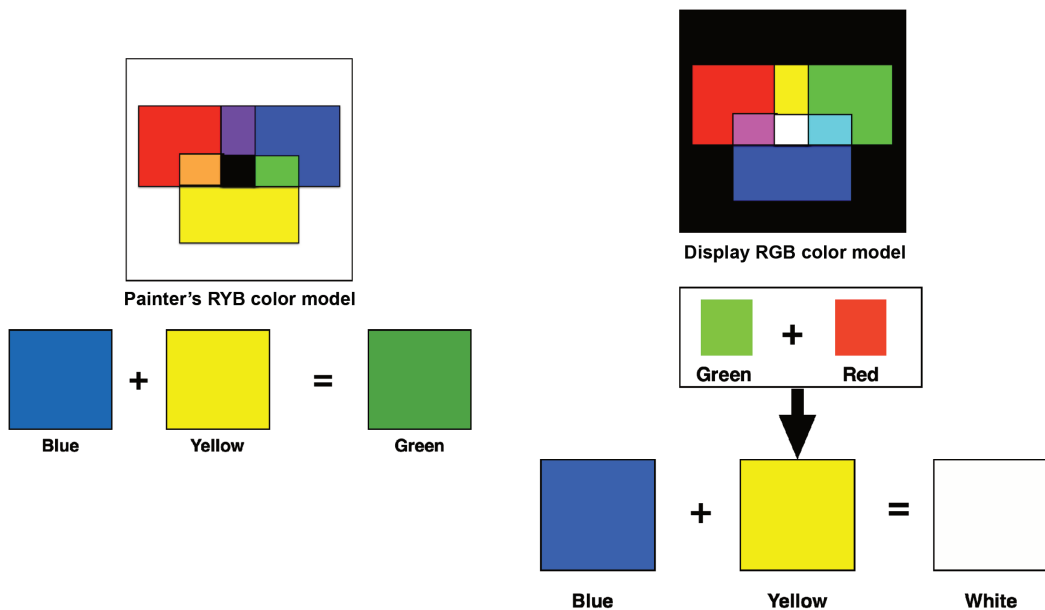


FIGURE 1.9 Comparison of how Blue and Yellow mix to form Green in the RYB painters color model versus forming White in the RGB display color model. Image created by Theresa-Marie Rhyne, 2024.

knowledge of RYB color theory. Therefore, Newton's observations were very misunderstood and frequently challenged by painters and other visual artists in the 18th century. It would not be until 19th-century developments of RGB color vision principles that the relationship between additive and subtractive color models, as shown in Figure 1.6, was understood. In the next section of this chapter, we will highlight the evolution of color theory based on the color wheel concepts introduced by Newton and later modified by 18th-century artists and scientists.

1.5 OVERVIEW OF THE HISTORICAL PROGRESSION OF COLOR

As noted in previous sections, Isaac Newton developed the initial concept of the color circle or the color wheel. His diagram, shown in Figure 1.10, was published in his 1704 book, entitled *Opticks*. Newton transitioned individual spectral colors, observed in his prism experiments, into a closed color circle. He selected seven colors to correspond to the musical concept that an octave displays seven sound intervals. Newton's decisions on specific colors were based on aesthetic preferences rather than on scientific principles. He chose Red, Orange, Yellow, Green, Blue (actually Cyan), Indigo (frequently referred to as Dark Blue), and Violet. Newton's *Opticks* book went on to become one of the most widely read



FIGURE 1.10 Adapted from Isaac Newton's color circle diagram that appeared in his 1704 *Opticks* book. We have added color squares to highlight Newton's text descriptions of colors noted in the circle diagram. Image adapted from Reference [1] by Theresa-Marie Rhyne, 2016.

scientific books of the 18th century. His rainbow color map concepts and the establishment of the color circle or color wheel continue to influence us even today. In Section 2.11 of Chapter 2, we will highlight some of the difficulties in using the rainbow or Newtonian color map as a default color scheme for current visualization and visual analytics efforts.

In 1766, over 60 years after Isaac Newton's writings on the color circle, Moses Harris published his *Natural System of Colours* book. Moses Harris was an entomologist and engraver in England. In his book, Harris described the RYB color model and demonstrated the wide variety of colors that result from combinations of the three primary colors [3]. His observations built upon the writings of Newton, as well as Jacob Christoph Le Blon's patented three-color separation printing process of 1719. Harris was particularly focused on the classification of colors and the relationships between specific colors. As a result, he made the first known published attempt to diagram the RYB color wheel. He defined a "prismatic" or primary color wheel for RYB, as well as a "compound" color wheel for the secondary colors of Orange, Green, and Purple. Harris's color wheels were divided into arc segments to diagram pure colors, as well as shades and tones. At the center of the wheel, the three primaries mix together to form Black. This would later be defined as a subtractive color model. Scientists, artists, and engravers valued Harris's color wheel since it served as a simplified and practical way to quickly visualize the relationships among colors and allowed for matching colors to existing samples. In Figure 1.11, we show Moses Harris's prismatic and compound color wheels.

In 1810, Johann Wolfgang von Goethe published *Zur Farbenlehre* (translated into English as *Theory of Colours*) that became a foundation for color theory in regard to the RYB color model. In his book, Goethe challenged many of Newton's writings on the physics

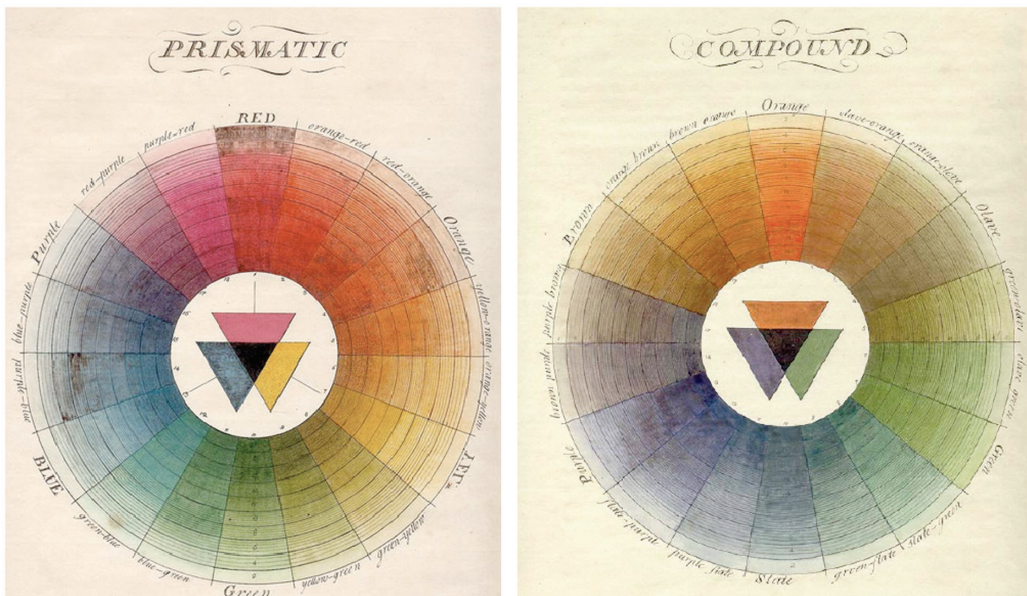


FIGURE 1.11 Prismatic and compound color wheels published by Moses Harris in “The Natural System of Colors”, Leicester-Fields: Laidler; 1766 [3]. Public domain.

of color and introduced a systematic exploration of the physiological and psychological effects of color. Goethe proposed a symmetric color wheel composed of colors that oppose or complement each other. His writings discussed how complementary colors cancel each other out to produce Gray or Black when mixed as pigments. He also noted that when two opposing colors are placed next to each other, humans perceive the highest or strongest contrast for these two particular colors. His diagram, shown here, included Yellow opposing Violet, Orange opposing Blue, and Green opposing Magenta. The inclusion of Magenta by Goethe was a departure from the Newtonian views of color. Magenta is a non-spectral color and thus was not included in Newton's definition of fundamental colors. Goethe viewed Magenta as the mixture of Violet and Red that completed the color circle or the color wheel. The role that Goethe defined for Magenta is still applied today in modern color systems. He also intentionally recognized the psychological effect of Magenta appearing as an afterimage resulting from intensely viewing Green. In Figure 1.12, we show Johann Wolfgang Goethe's color wheel of complementary or opposing colors.

Goethe's book was a catalog of his color studies and observations. He also noted Red and Green as complementary pigments in regard to the RYB color model. It appears Goethe slightly merged additive color concepts of what later became the RGB color model of lights with subtractive concepts of the RYB color model of pigments in his many observations. These kinds of inconsistencies and Goethe's direct attack on Newton's color observations resulted in scientists dismissing many aspects of Goethe's book. In 1840, Charles Eastlake published an English translation of Goethe's *Zur Farbenlehre* book and entitled it *Theory*

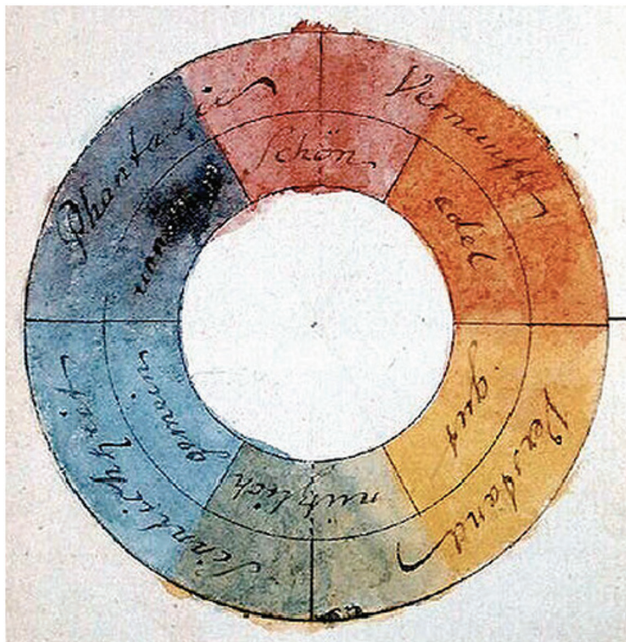


FIGURE 1.12 Johann Wolfgang von Goethe's color wheel that appeared in "Goethe's Theory of Colours", translated with notes by Charles Lock Eastlake, R.A. F.R.S. London: John Murray; 1840 (<https://archive.org/details/goethestheoryco01goetgoog>) [4]. Public domain.

of *Colours*. Eastlake, in his English version, omitted many of Goethe's statements that challenged Newton's color observations [4]. This allowed the reader to focus more directly on the physiological and psychological color studies noted by Goethe. Painters embraced Eastlake's translation of *Goethe's Theory of Colours*. Goethe's writings went on to become widely adopted as one of the foundations of color theory by the art world.

In 1824, Michel Chevreul, a highly regarded French chemist, was appointed as the director of the dyeing department at the Gobelin tapestry factory. His chief task was to investigate the causes of fading in tapestry threads. Chevreul realized that the difficulties were not with the dyes but rather with the simultaneous color contrast between adjacent threads. After four years of study, in 1828, Chevreul published his first paper on his observations, entitled "Memoir on the influence that two colours can have on each other when seen simultaneously". In 1839, after much effort to achieve effective color reproduction of his diagrams, Chevreul published his book *De la Loi du Contraste Simultané des Couleurs*. The French book was translated into German, English, and other languages. In 1854, Charles Martel published an English translation entitled *The Principles of Harmony and Contrast of Colours, and their Application to the Arts* [5]. Additionally, Chevreul went on to publish three other books on color. Chevreul's books were widely read by painters and other artists who applied his concepts in their image creation and design processes. His writings on the color harmony and simultaneous contrast are considered part of the foundations of color theory that are still applied today. We work through an example in Figure 1.13.

In this example, we consider Orange and Cyan squares placed next to each other and inside each other. These hues have high contrast according to the RYB color model. Notice that the Cyan (Light Blue) square on the Orange background appears larger than the Orange square on the Cyan background. The two colors also appear to amplify or intensify each other as we view the colors together. We perceive these colors as altered; however, the



FIGURE 1.13 Example of the simultaneous contrast between Orange and Cyan (Light Blue) squares. Image created by Theresa-Marie Rhyne, 2016.



FIGURE 1.14 Michel Eugène Chevreul’s color wheel or chromatic diagram that emphasizes complementary (opposing) colors. The complementary colors are directly across from each other on the color wheel. Published in Reference [5]. Public domain.

hues have not actually changed. These are some of the simultaneous contrast elements that Chevreul presented in his books.

In his writings on color, Chevreul diagrammed a color wheel with twelve main color units of Red, Reddish Orange, Orange, Orange Yellow, Yellow, Yellowish Green, Green, Greenish Blue, Blue, Violet Blue, Violet, and Violet Red with six zones in each color unit. This resulted in a total of 72 segments for his color wheel based on the RYB color model. Complementary (e.g., intensely contrasting) colors were placed directly opposite to each other on the color wheel. Chevreul called this color wheel a “chromatic diagram”. We show an example from his first book on *The Principles of Harmony and Contrast of Colours, and their Application to the Arts* as Figure 1.14.

1.6 AN EXAMPLE OF COLOR THEORY APPLICATION

Here, we show an example of the application of our simultaneous contrast knowledge to a visualization problem. Our task is to develop a color scheme for a *treemap* visualization. In the field of information visualization, a treemap permits the display of hierarchical data by creating a set of nested squares. Each branch of the tree is defined with a rectangle and tiled with smaller rectangles that represent sub-branches. Color and size dimensions of rectangles are correlated with the tree structure. This allows for seeing patterns in the data that would be challenging to detect in other ways. Treemaps can effectively display thousands of items simultaneously. Ben Shneiderman at the University of Maryland’s Human–Computer Interaction Lab invented the treemap visualization method in the 1990s [6].

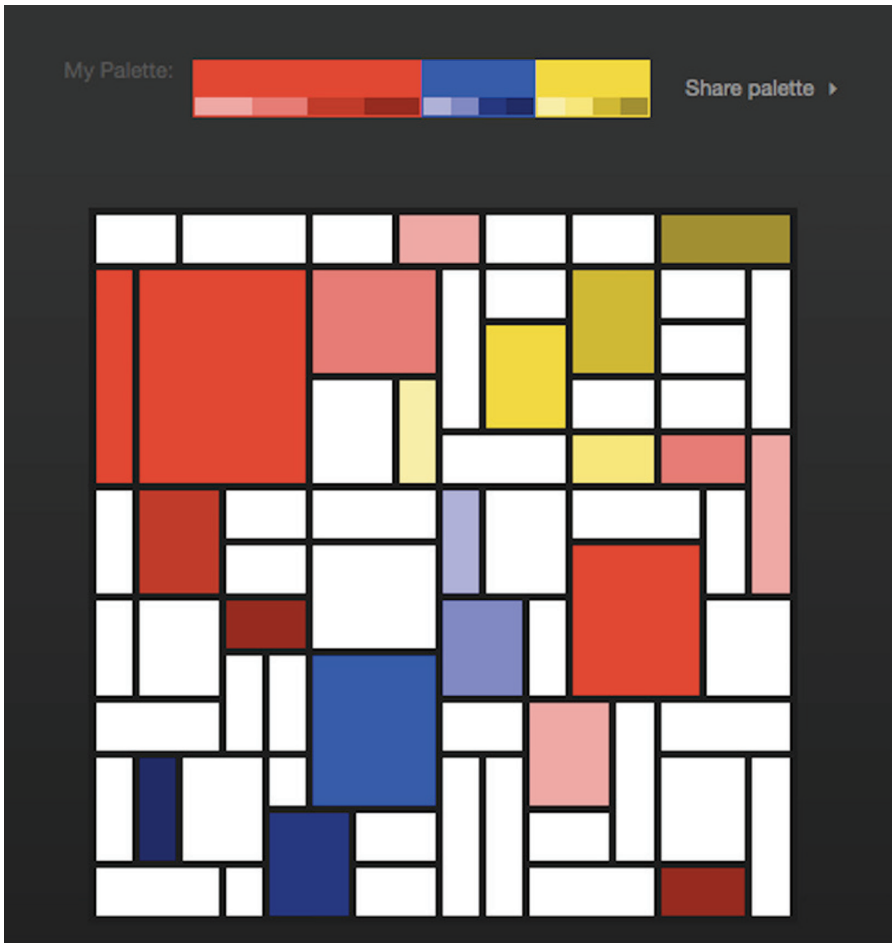


FIGURE 1.15 Red, Yellow, and Blue color scheme design using a display structure similar to the paintings of Piet Mondrian. We used Paletton’s Color Scheme Designer to create this image [8]. Image created by Theresa-Marie Rhyne, 2016, updated in 2024.

Returning to our task of building a color scheme for a treemap visualization, we recall that the artist, Piet Mondrian, also worked in squares and rectangles [7]. In his paintings, Mondrian preferred to use the primary colors of the RYB color model. In Figure 1.15, we show a color display structure similar to the paintings of Mondrian that we created with Paletton’s Color Scheme Designer [8]. Color Scheme Designer is an online tool for creating color schemes that we will discuss further in Chapter 6 of this book.

For our treemap visualization, we need two colors and decide to apply an Orange and Cyan (Light Blue) complementary color structure noted in Goethe’s writings. However, we recall the concepts of the simultaneous contrast noted by Chevreul and shown in Figure 1.13. As a result, we do not place these colors precisely adjacent to or inside of each other, include varying sizes of our rectangles, and reduce the color brightness of our color selections. In Figure 1.16, we show the Mondrian-like Orange and Cyan color map created with Color Scheme Designer on the left. On the right, in Figure 1.16, we show the

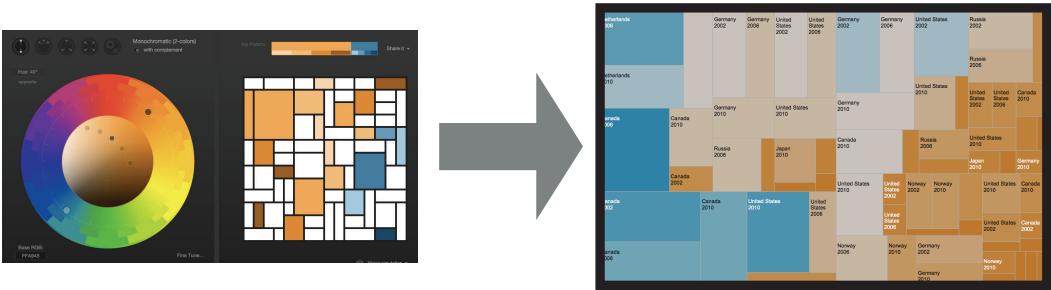


FIGURE 1.16 Example of Color Theory Application using an Orange and Cyan complementary color scheme. We have controlled hue tones and the placement of the two colors to reduce the simultaneous contrast. We used Paletton's Color Scheme Designer Tool to create the Mondrian-like image shown on the left [8]. We used Tableau Public Software to create the treemap visualization shown on the right [9]. Images created by Theresa-Marie Rhyne, 2016, updated in 2024.

application of the Orange and Cyan color scheme to a treemap visualization created with Tableau Public Software (<https://public.tableau.com/s/>). Tableau Public Software is a freely available tool for building visualizations, especially from tabular data. Tableau Software Inc. created this software that we note in Reference [9].

1.7 PERCEPTUAL LIMITATIONS OF THESE COLOR MODELS REGARDING HUMAN VISION

As noted previously in this chapter, the RGB color model focuses on viewing displays like what we see on our desktop and mobile devices, the CMYK color model is designed for color printing, and the RYB color model has a long historical use by artists for mixing paints and dyes in creating visual compositions. None of these color models are perceptual models optimized for the human visual system. Human perception issues were examined in the late 1890s by Albert H. Munsell, an American artist and educator, when he developed his own color system [10]. By the 1990s, the data visualization community began to note the potential for artifacts in data with the RGB color model [11]. In Chapters 2 and 3 of this book, we will discuss these matters and show color systems designed and optimized for human perception.

1.8 CONCLUDING REMARKS

In this chapter, we reviewed the following three key color models: (1) the RGB color model for displays, (2) the CMYK color model for printing, and (3) the RYB color model for paints. A few color mixing challenges when moving between color models were highlighted. Next, we provided a brief overview of the historical progression of color theory. We will revisit the historical evolution of the color wheel and color harmony in Chapter 4. In Chapter 2, we will focus on color vision concepts that are key to furthering our understanding of human color perception.

REFERENCES

1. Newton, S.I. (1704), *Opticks: Or, a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light. Also Two Treatises of the Species and Magnituder of Curvilinear Figures*, London: Samuel Smith and Benjamin Walford. Available from The Project Gutenberg EBook of Opticks: <https://www.gutenberg.org/files/33504/33504-h/33504-h.htm>.
2. “The Theory of the Primary Colors”, the *British Journal of Photography*, August 9, 1861, https://notesonphotographs.org/index.php?title=%22The_Theory_of_the_Primary_Colours.%22_The_British_Journal_of_Photography,_August_9,_1861.
3. Harris, M. (1766), *The Natural System of Colors*, Leicester-Fields: Laidler.
4. von Goethe, J.W. (1840), “Goethe’s Theory of Colours”, Translated with notes by Charles Lock Eastlake, R.A. F.R.S., London: John Murray. <https://archive.org/details/goethetheoryco01goetgoog>.
5. Chevreul, M.E. (1839), *De la loi du contraste simultané des couleurs et de l’assortiment des objets colorés*, Paris, English transl. by Charles Martel as *The Principles of Harmony and Contrast of Colours*, London: Longman, Brown, Green and Longmans, 1854.
6. Johnson, B. and Shneiderman, B. (1991), “Tree-maps: A space-filling approach to the visualization of hierarchical information structures.” In *IEEE Conference on Visualization, 1991. Visualization’91, Proceedings*, pp. 284–291, San Diego, CA, IEEE.
7. Mondrian, P. (1986), “The new art – The new life: The collected writings of Piet Mondrian”, *Documents of 20th-Century Art*, H Holtzman and MS James, eds., Boston: G. K. Hall and Co; ISBN 0-8057-9957-5. Reprinted 1987, London: Thames and Hudson. ISBN 0-500-60011-2. Reprinted 1993, New York: Da Capo Press. ISBN 0-306-80508-1.
8. Paletton (2016 & 2024), *Color Scheme Designer*, <https://www.paletton.com>, 1st ed., Accessed March 8, 2016; 2nd ed., Accessed February 7, 2024.
9. Tableau Software (2016 & 2024), “Tableau Public Software”, <https://public.tableau.com/s/>, 1st ed., Accessed March 8, 2016; 2nd ed., Accessed February 7, 2024.
10. Munsell, A.H. (1905), *A Color Notation*, Boston, MA: G.H. Ellis Company.
11. Rogowitz, B.E. and Treinish, L.A. (1998), Data visualization: The end of the rainbow. *IEEE Spectrum*, 35 (12), 52–29.

Review of Color Vision Principles

2.1 THE VISIBLE LIGHT SPECTRUM

In scientific terms, color is both a psychological and a physiological response to light waves of specific frequencies that strike our eyes. Human eyes are sensitive to a narrow subset of the broad range of frequencies in the electromagnetic spectrum. This is called the *visible light* spectrum. Visible light, detectable by humans, ranges from wavelengths of approximately 390 to 780 nm [1]. Specific wavelengths within the visible light spectrum correspond to specific colors. As we discussed in Chapter 1, Isaac Newton defined the visible spectrum as ranging from short wavelengths of Violet to long wavelengths of Red with Indigo (Dark Blue), Blue (actually Cyan), Green, Yellow, and Orange being the colors in between. In Figure 2.1, we show the approximate range of wavelengths that correspond to perceived colors in the visible light spectrum. Figure 2.1 begins with the short waves of

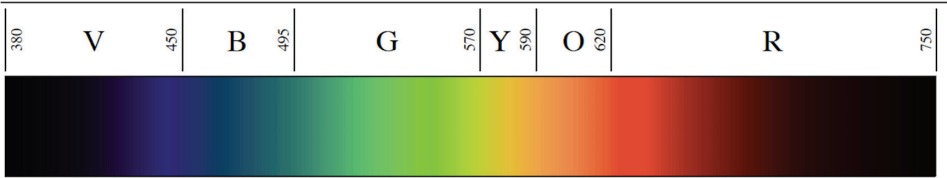


FIGURE 2.1 Representation of the visible light spectrum. This diagram moves from short waves of 380nm in the Violet range to 750nm in the Red range. The colors span from Violet, Blue, Green, Yellow, Orange, to Red. Color ranges were specified according to the *CRC Handbook of Fundamental Spectroscopic Correlation Charts*. This representation does not specify the Blue (actually Cyan) light that Newton noted in his original writings. See Section 1.1 of Chapter 1 for further details on Newton’s presentation of the color spectrum. Source: image created by Gringer in 2008 and is in the public domain by request of the creator, https://commons.wikimedia.org/wiki/File:Linear_visible_spectrum.svg.

Violet and ends with the long waves of Red. This representation does not specify the Indigo color, between Violet and Blue, that Newton noted in his original writings.

2.2 HUMAN VISION FUNDAMENTALS

The key biological components of vision are the eye, the visual center in the brain, and the optic nerve that connects the two. Light enters the eye through the pupil. Behind the pupil of the eye is the lens. The lens behaves similar to a camera lens. In conjunction with the eye's cornea, the lens adjusts the focal length of the image that strikes the inside surface of the eye called the retina. The lens of the eye reverses images as it focuses on them. The direct images on the retina are upside down, and the visual center of the brain flips the images back over to interpret what we see. Figure 2.2 shows the anatomy of the eye. In addition to the key components for vision, Figure 2.2 also notes the conjunctiva that lines the inside of the eyelid and covers the sclera (the White part) of the eye, as well as the iris that controls the diameter and size of the pupil. The iris controls the amount of light reaching the retina, and the color of the iris gives the eye its color.

The retina is lined with rods and cones that serve as light sensors and are called photoreceptor cells. Combined, the rods and cones cover the complete range of the eye's adaption to light. Together, they gather the information that our brain interprets into one combined image. The rods are sensitive to the intensity of light but do not distinguish between lights of varying wavelengths. The rods are located at the edge of the retina and work in a dim light to provide us a coarse sketch of the world around us. The rods are far more numerous

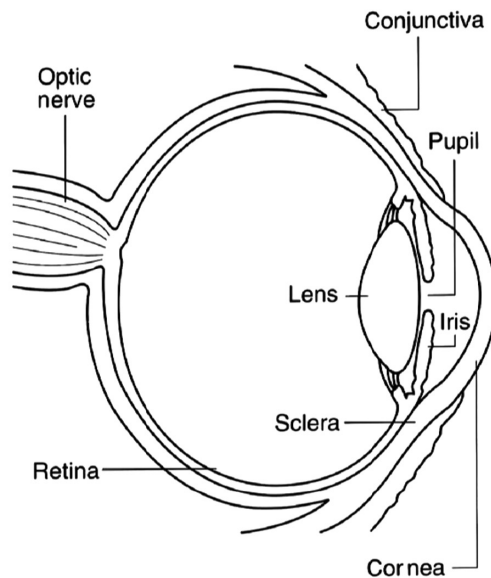


FIGURE 2.2 Here, we show the anatomy of the eye. The vision process in humans involves light entering the eye through the pupil and then striking the inside surface of the eye called the retina. Source: the National Eye Institute, National Institutes of Health, USA, July 10, 2012, <https://medialibrary.nei.nih.gov/search?keywords=&f%5B0%5D=category%3A6&page=0>. Public domain.

than cones but are out of commission in a bright light. The cones are clustered at the center of the retina, called the fovea, and work in a bright light. The cones are the color-sensing cells of the retina and are responsible for our ability to see fine details. When light of a specific wavelength enters the pupil and strikes the cones of the retina, a chemical reaction results with the optic nerve sending electrical impulses to the brain. The brain interprets these electrical impulses of the cones as various colors [2].

2.3 TRICHROMATIC COLOR VISION

Color vision is thus a function of the cones. The theory of *trichromatic* color vision asserts that there are three types of cones and each is optimized to absorb a different spectrum range of visible light [3]. One set of cones absorbs long waves of light in the Red range. A second set of cones absorbs middle waves of light in the Green range. The third set of cones absorbs short waves of light in the Blue range. We covered the contributions of Thomas Young and Herman von Helmholtz to the theory of trichromatic color vision in our discussion of the Red, Green, and Blue (RGB) color model in Chapter 1 of this book. As we noted, James Clerk Maxwell’s demonstration of the RGB color model during his 1861 lecture at the Royal Institute in the United Kingdom was considered “proof” of Young’s and Helmholtz’s assertions. In Figure 2.3, we show a diagram of the theory of trichromatic color vision. In Figure 2.3, the Blue cones with short wavelengths are shown on the left, the Green cones with medium wavelengths are shown in the middle, and the Red cones with longer wavelengths are shown on the right. This corresponds to the left-to-right progression of the visible light spectrum shown previously in Figure 2.1.

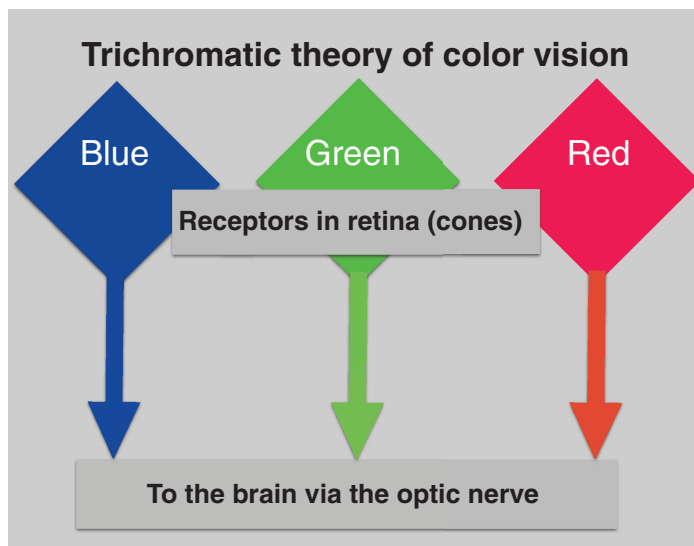


FIGURE 2.3 Diagram of the trichromatic theory of color vision. The Blue cones with short wavelengths are shown on the left, the Green cones with medium wavelengths are shown in the middle, and the Red cones with longer wavelengths are shown on the right. This corresponds to the left-to-right progression of the visible light spectrum shown previously in Figure 2.1. Source: illustration by Theresa-Marie Rhyne, 2015.

2.4 OPPONENT COLOR THEORY

In 1878, Ewald Hering, a German physiologist, published *On the Theory of Sensibility to Light in Vienna* where he challenged the Young and Helmholtz theory of trichromatic color vision [4]. Hering opposed the purely physiological understanding of the RGB color model. Hering proposed that color vision occurred in three channels where opposite colors are in competition. The channels are (1) a Red-Green channel, (2) a Yellow-Blue channel, and (3) a Black-White channel. The Black-White channel, or achromatic system, addresses the brightness contrast. Together, the Red-Green channel and Yellow-Blue channel create a chromatic system for the color contrast. Hering postulated that there were four primary colors with Red and Green opposing each other and Yellow and Blue opposing each other. In his writings, Hering noted that we do not see Reddish Green combinations of color. The same is true for Yellow and Blue, and we do not see Yellowish Blue combinations of color. In Figure 2.4, we diagram Hering's *opponent color theory*.

The assertion that Yellow was a primary color was controversial given the wide acceptance of trichromatic color vision in the scientific community of the late 1800s. Hering's premise was that our psychological experience produces four distinct color hues from which all other colors are mixed. Hering based some of his opponent processing theory on color afterimages. For example, Red and Green are opposite colors. If we focus our vision on a Red dot and then gaze at a White wall, we will see a Green dot as an afterimage. Reversely, if we focus on a Green dot and gaze at a White wall, we will see a Red dot afterimage. The same results occur for Blue and Yellow. In Figure 2.5, we show two examples of afterimage studies.

Ewald Hering and Herman von Helmholtz were contemporaries who argued intensely among each other regarding the differences between trichromatic color vision and opponent

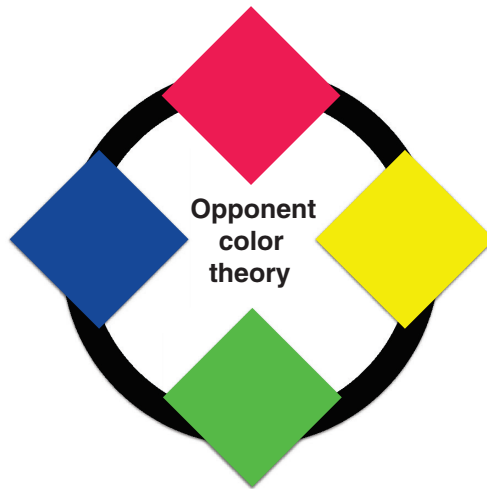


FIGURE 2.4 Diagram of Ewald Hering's opponent color theory concept. With opponent color theory, there are four primary colors with Red and Green opposing each other and Yellow and Blue opposing each other. This becomes a chromatic system for color contrast. Source: illustration by Theresa-Marie Rhyne, 2015.

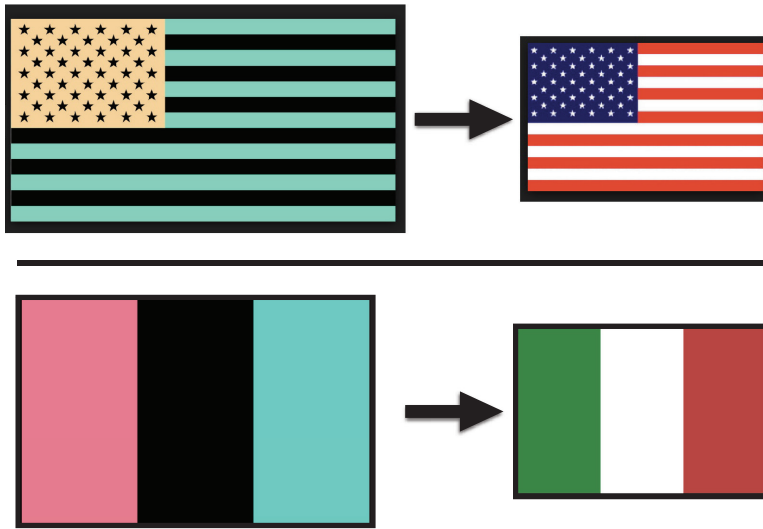
Afterimage studies:

FIGURE 2.5 Examples of afterimage studies. Stare at each individual image on the left for 60 seconds and look away to a blank wall. The results should be the images on the right. Source: public domain images and examples, redrawn by Theresa-Marie Rhyne, 2016.

processing color theory. Each viewpoint appeared to have credibility in explaining some aspects of color vision. In 1957, while doing work for Eastman Kodak, Leo Hurvich and Dorothea Jameson provided quantitative data to support Hering's opponent processing color theory. Hurvich and Jameson defined the concept of "hue cancellation methods" [5]. Their research showed (1) Red and Green lights mixed together produce a Yellow light, not Reddish Green; (2) Blue and Yellow lights mixed together produces a White light, not Yellowish Blue; and (3) Red and Green cancel each other as do Yellow and Blue. Their findings also noted that starting with Bluish Green, it is possible to mix the Yellow light with the Bluish Green light to cancel out Blue. This results in the production of a Green light. Hurvich and Jameson also showed that trichromatic color vision co-existed with opponent processing color theory. Helmholtz and Hering both had valid theories of color vision. Young and Helmholtz's theory of trichromatic color vision explains what happens with our eyes at the photoreceptor level. Hering's opponent processing color theory explains aspects of color vision processing at the neural level when images are transferred from the eye to the brain via the optic nerve.

2.5 TRICHROMACY, METAMERISM, AND COLOR CONSTANCY

As we have shown, the operation of our three cones is more complex than the Red, Green, and Blue color model might indicate with trichromatic color vision co-existing with opponent processing color theory. Each of the retina's three types of cones contains a different kind of a photosensitive pigment. The pigments are composed of a transmembrane protein called opsin and a light-sensitive molecule called 11-cis-retinal [6]. Each different pigment is sensitive to certain wavelengths of light. The Red cones in our eyes are sensitive

to a range of long wavelengths. This means that the Red cones are not only activated by wavelengths of a Red light but, to a lesser extent, also can be activated by wavelengths of Orange, Yellow, and even Green lights. Interestingly, the Red cones have their peak sensitivity in the Green-to-Yellow range of the visible spectrum. The Green cones, while being most sensitive to medium wavelengths of a Green light, can also be activated by Yellow and Blue lights. The Green cones have their peak sensitivity in the Green wavelength range. The Blue cones are sensitive to short wavelengths of Violet and Blue lights and have their peak sensitivity in the Violet-to-Blue wavelength zone. The responses of the three types of cones to light are called physiological responses. Trichromacy is the technical term for our condition of having three independent channels for conveying color information to our brain. Figure 2.6 diagrams the spectral sensitivity curves of our three types of cones to help depict the response to light as it strikes the retina [7].

The response of a specific type of cone varies by wavelength and intensity of the light. This information is transferred by the optic nerve to the brain. The brain is unable to discriminate different colors with input from only one type of cone. The interaction between at least two types of cones is needed for the brain to have the capability to perceive color. With information from at least two types of cones, the brain compares the signals from each type of cone and assesses the intensity and color of the light. Humans have three types of cones to support this activity. The brain's processing of the electrical messages

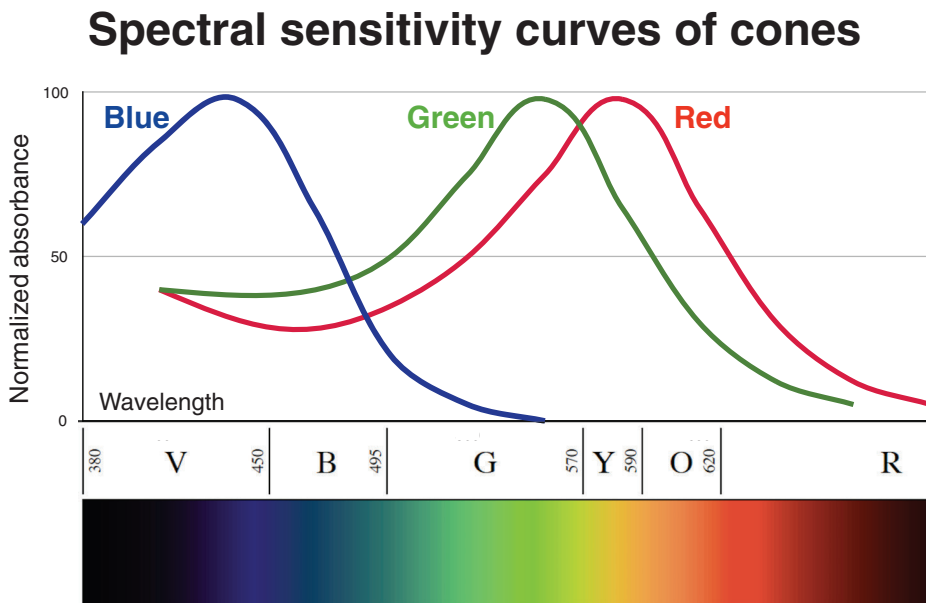


FIGURE 2.6 Spectral sensitivity curve diagrams for long-wave cone (Red), medium-wave cone (Green), and short-wave cone (Blue) responses. Color spectrum image created by Gringer in 2008 and in the public domain by request of the creator, https://commons.wikimedia.org/wiki/File:Linear_visible_spectrum.svg. Source: spectral sensitivity curves adapted from Bowmaker & Dartnall [6] and drawn by Theresa-Marie Rhyne, 2015.

sent by all three types of cones is called the psychological response to light. The sensitivity of our cones to long, medium, and short wavelengths is used to define the concept of LMS (long, medium, and short) color space. The LMS color space is useful in the study of color deficiencies where one or more cone types are defective. We will cover color deficiencies in Section 2.8.

We work through an example of a Yellow light to help clarify the concepts we have presented previously. Let us assume that a set of Yellow wavelengths (in the range of 577–597 nm) enters the eye and strikes the retina. A light with these wavelengths then activates the Red and Green sets of cones to produce the physiological response of electrical messages. The optic nerve sends the electrical messages to the brain. The brain then recognizes that Red and Green cones were simultaneously activated and interprets this to mean that the color Yellow was observed. The lack of response from the Blue cones confirms this interpretation even further. As we have noted previously in describing opponent processing color theory, we do not see Yellow and Blue together. This is the psychological response to the Yellow light [7].

We can also add complexity to this example by addressing the mixing of two different visible light wavelengths. Suppose we send lights of Red wavelengths and lights of Green wavelengths to the eye simultaneously. The Red light would primarily activate the Red cones, while the Green light would primarily activate the Green cones. Each set of cones would send their physiological messages to the brain via the optic nerve. The brain, trained to perceive the two simultaneous Red and Green signals to mean Yellow, would send a psychological response indicating that a Yellow light has been received. The brain has no means of distinguishing between a set of single Yellow wavelengths and a set of

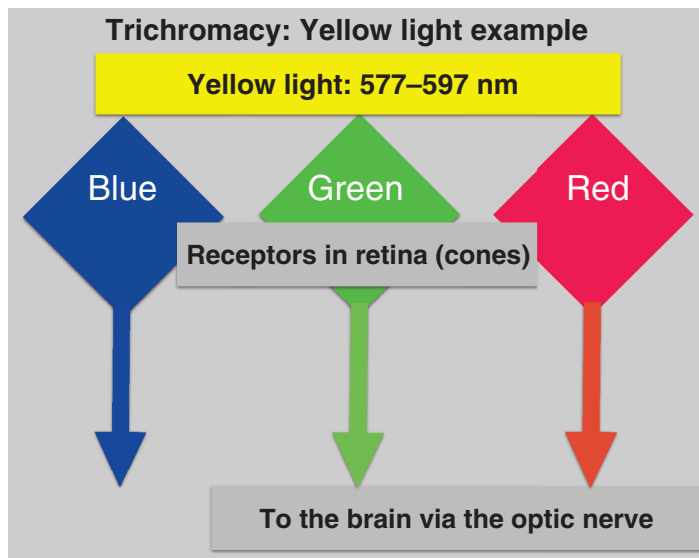


FIGURE 2.7 Diagram of trichromacy for a Yellow light example. Humans have three independent channels for conveying color information to the brain, and this is called trichromacy. For a Yellow light, only the Green and Red channels operate. Source: illustration by Theresa-Marie Rhyne, 2015.

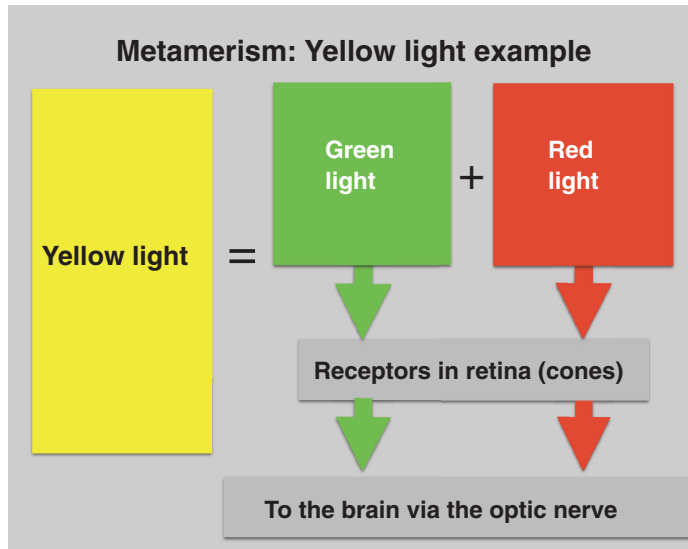


FIGURE 2.8 Diagram of metamerism for a Yellow light example. Metamerism is generally defined as the matching of the color of an object (for this case, Yellow) with spectral power distributions that are different from one another (for this case, Red and Green). The brain has no means of distinguishing between a set of single Yellow wavelengths and a set of Red and Green wavelengths combined to generate Yellow. Source: illustration by Theresa-Marie Rhyne, 2015.

Red and Green wavelengths combined. The combination of Red and Green lights to produce the equivalent of a Yellow light is an example of the principle of *metamerism* [8]. Metamerism for color is generally defined as the matching of the apparent color of an object (for our case, Yellow) with spectral power distributions that are different from one another (for our case, Red and Green). Figure 2.8 diagrams the concept of metamerism for a Yellow light.

Metamerism is a key concept in working with the Red, Green, and Blue (RGB) color model that we covered earlier in Chapter 1. The combination of Red, Green, and Blue lights to create a combined color value is used in displays for electronic systems, like digital cameras, televisions, computer and mobile phone displays, and video projectors [9]. For these displays, each pixel on the screen combines three small and very close but slightly separated RGB light sources. The separate sources of Red, Green, and Blue lights are indistinguishable at common viewing distances so that our eye–brain color vision system perceives solid color. As noted earlier in this section, *trichromacy* is the term that describes our three channels for color associated with the three cones in our eyes. This principle of trichromacy is further applied to the RGB color model where color is described by the three values of Red, Green, and Blue. The concept of defining a color in terms of RGB values is frequently used in color science and is shown in Figure 2.9.

As we have noted, it is possible to create Yellow from Red and Green lights with Blue lights equaling zero. For our example in Figure 2.9, Yellow is defined in RGB values as 255, 255, 0. The highest value in this case is 255, and the lowest value is 0. The use of the range of 0–255 to define digital (RGB) color is actually based on the computer memory. The color

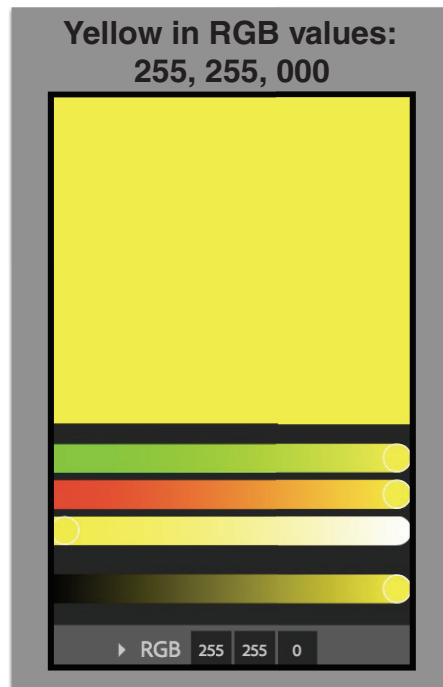
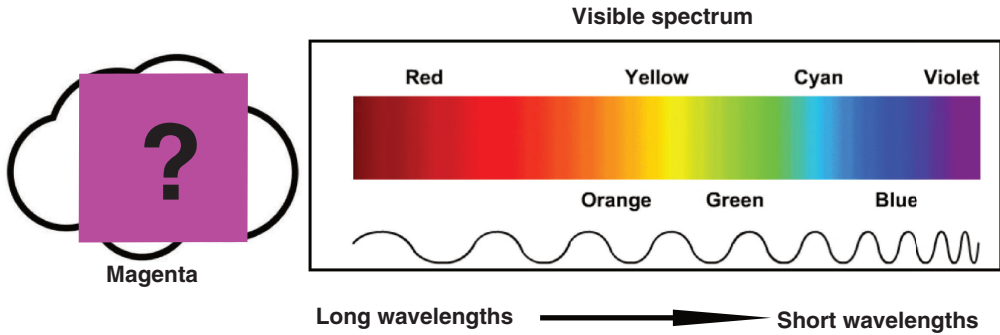


FIGURE 2.9 Diagram of the color Yellow in RGB values of Red=255, Green=255, and Blue=0. Adobe Color (<http://color.adobe.com>) was used to capture the RGB values for this figure. We define the color of Yellow by using only Red and Green lights with Blue lights equaling zero. Source: illustration created by Theresa-Marie Rhyne, 2015.

for a given object is stored in a computer's memory. This computer memory is in the form of on and off switches defined in terms of a long sequence of 0's and 1's. Each switch is called a bit, and 8 bits form a byte. If there are 8 bits (1 byte) in a sequence, there are 256 possibilities to configure these switches. This yields a range of numbers between 0 and 255.

Our human color perception system provides us with the ability to comprehend the color of objects irrespective of the light source used to illuminate them. For example, we identify the same Yellow color of a banana under bright sunlight, fluorescent lighting, or candlelight. Even though the surrounding light source might cause more Orange hues or perhaps Green hues to actually reach our eyes, our brain works to correct this situation to keep the Yellow color of the banana constant. This phenomenon is called color constancy. Our brain disregards the continual changes in the wavelengths of light reflected from a surface. This stability in color allows us to categorize color-related properties of objects consistently as we transition through our daily processes of living.

From a precise technical viewpoint, it is actually inappropriate to refer to light as having color [6]. Basically, light is a wave with either a specific wavelength or a mixture of wavelengths. Light has no color itself. Rather, an object that emits or reflects light appears to have color to our eyes. This is due to both our physiological and psychological eye-brain responses to the wavelength. Returning to our Yellow light example, there is a light in the range of 577–597 nm that appears Yellow. Although technically imprecise, we will refer to



Magenta is visibly in our human brains between Violet and Red. However, it is not a visible spectrum color with a wavelength.

FIGURE 2.10 Illustration of the concept that Magenta is visible in our human brains between Violet and Red, but is not in the visible light spectrum with a wavelength. Source: illustration created by Theresa-Marie Rhyne, 2024.

Yellow and other colors of light as we further develop concepts for applying color theory to digital media and visualization in this book.

Another color of interest here is Magenta. Looking closely at the visible light spectrum, Magenta is not one of the colors that spans from Violet, Blue, Green, Yellow, Orange, to Red. Visually, we are certain that Magenta is a color between Violet and Red, but it has no specific wavelength. How can this be? In Chapter 1, we noted that in 1810, Johann Wolfgang von Goethe published a color wheel that recognized Magenta as a color between Violet and Red. Goethe was interested in the physiological and psychological effects of color. He and others after him acknowledged that Magenta is a color that our brains create to logically fill in the color gap between Violet and Red. However, Magenta is not part of the visible light spectrum with a wavelength. Figure 2.10 illustrates the mysterious nature of Magenta.

The biology of our color vision is highly complex and still under study even today. We have only provided an overview regarding how to apply these concepts to creating effective digital media and visualization content. In Section 2.8 of this chapter, we will discuss color vision deficiencies and how to incorporate this knowledge into the design of digital media.

2.6 LUMINOSITY

Luminosity is the perceived brightness of a color. Perceived brightness is not necessarily a numerical or measured value associated with a given color model. In Figure 2.11, we show the Red, Green, and Blue colors in full strength (at a 255 value for each hue) side by side as three individual swatches. The majority of viewers of Figure 2.11 would agree that the Green color is perceptually lighter or more luminous than the Red hue. The Red color is in turn lighter than the Blue hue. Although the numeric values indicate 100% brightness or luminosity (255 respectively), we perceive different tones. If we convert the same image

Luminosity comparison of Red, Green, and Blue colors with equal full strength (255) values:



FIGURE 2.11 Study in luminosity where the Red, Green, and Blue (RGB) colors at equal full strength (255 values) are placed side by side. Adobe Color (<http://color.adobe.com>) was used to create this figure. For the majority of viewers, the Green color is perceptually lighter and more luminous than the Red color. The Red color is in turn lighter than the Blue color. If we convert the same figure to a Black-and-White image where the luminosity becomes 0% (000 respectively), we see the brightness of the Red, Green, and Blue colors become equal. Source: illustration created by Theresa-Marie Rhyne, 2015.

to a Black-and-White image where the luminosity becomes 0% (000 respectively), we see the brightness of the Red, Green, and Blue colors becomes equal. Differences in perceived luminosity become key parameters in assessing colorimetry data provided by human subjects and the development of the color spaces and systems. Color spaces and systems are discussed further in Chapter 3.

2.7 CHROMATICITY

Chromaticity is defined as an objective specification of the quality of a given color irrespective of the given color's luminance. Chromaticity is specified by two independent parameters frequently noted as hue and colorfulness where colorfulness is also defined as saturation, chroma, intensity, or purity depending on the particular color space under discussion. In Chapter 3, we will define and cover many color spaces that use differing colorfulness parameters. These include (1) hue, saturation, and value (HSV); (2) hue, saturation,

and lightness (HSL); (3) the Munsell color system; (4) the CIE 1931 XYZ color space; (5) the CIE LUV and CIE LAB color spaces; and (6) the hue, chroma, and luminance (HCL) color spaces.

2.8 COLOR VISION DEFICIENCIES

As noted previously, color vision is possible due to the cones or photoreceptors in the retina of the eye. In humans, the existence of three types of photopigments where each is sensitive to different parts of the visual spectrum of light provides for a rich color vision. Pigments inside the cones register differing colors that are sent through the optic nerve to the brain. Since the eye and the brain work together to translate light into color, each person sees color differently. For individuals with normal color vision, these differences are slight. However, if the cones lack one or more of the light-sensitive pigments, it is not possible for the eye to view one or more of the Red, Green, and Blue primary colors [10]. This is defined as a *color vision deficiency* or as a type of color blindness.

The most common types of color blindness are considered to be hereditary and result from defects in genes that contain instructions for producing the photopigments found in cones [11]. These genes for photopigment production are carried on the X chromosome. Only one of the X chromosomes is sufficient to produce the required photoreceptors for color vision. If these genes are missing or damaged, the probability is higher that a color deficiency will appear in males rather than in females. This is due to males having only one X chromosome and females having two X chromosomes. A color deficiency can also be produced by the physical or chemical damage to the eye, optic nerve, or parts of the brain [12]. Below, we highlight (1) Red-Green, (2) Blue-Yellow, (3) color monochromacy, and (4) rod monochromacy deficiencies.

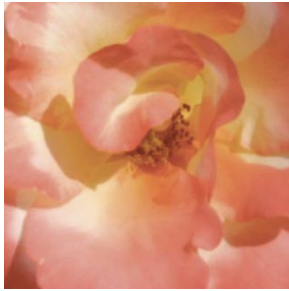
2.8.1 Red Cone Color Deficiency

The most common form of color vision deficiency is Red-Green. Red-Green hereditary color blindness can be due to (1) the limited function or loss of the Red cone (called protan) or (2) the limited function or loss of the Green cone (called deutan) photopigments. Protanomaly and protanopia are Red cone photopigment disorders. With protanomaly, the Red cone is abnormal with Red, Orange, and Yellow hues appearing Greener in tone. Individuals with protanomaly may also note that colors appear duller than individuals with normal color vision. This is considered a mild color deficiency that rarely interferes with daily living and is projected to affect 1% of males. Protanopia, a more severe color deficiency, involves no working Red cone cells. Red appears as Black, and some shades of Orange, Yellow, and Green appear as Yellow. Protanopia is estimated to affect 1% of the male population. Figure 2.12 depicts a Red cone color deficiency simulation created using the Coblis color blindness simulation tool.

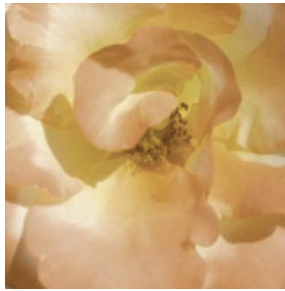
2.8.2 Green Cone Color Deficiency

Deuteranomaly, where the Green cone is abnormal, is the most common form of color deficiency. With deuteranomaly, Yellow and Green appear Redder and it is difficult to differentiate Violet from Blue. This color deficiency affects about 5% of males and is considered

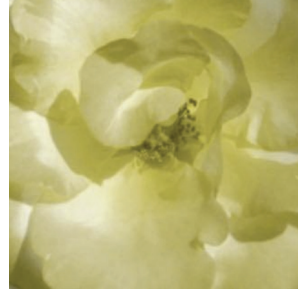
Red cone color deficiency simulation



Normal vision



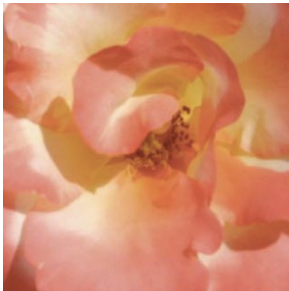
**Protanomaly:
Limited loss
of Red cone**



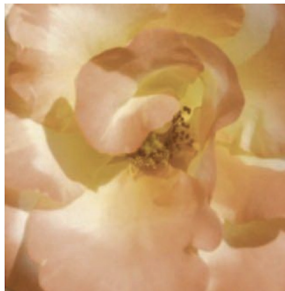
**Protanopia:
Severe loss
of Red cone**

FIGURE 2.12 Red cone color deficiency simulation: using the Coblis color blindness simulation tool, we depict an Orange and Yellow rose under normal vision, limited loss of the Red cone (protanomaly) vision, and severe loss of the Red cone (protanopia) vision. Coblis is available online at www.color-blindness.com/coblis-color-blindness-simulator/. Source: illustration created by Theresa-Marie Rhyne, 2015.

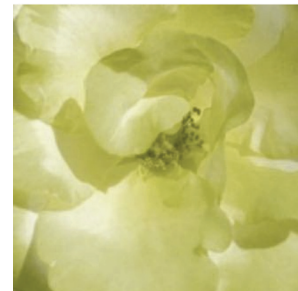
Green cone color deficiency simulation



Normal vision



**Deuteranomaly:
Limited loss of
Green cone**



**Deuteranopia:
Severe loss of
Green cone**

FIGURE 2.13 Green cone color deficiency simulation: using the Coblis color blindness simulation tool, we depict an Orange and Yellow rose under normal vision, limited loss of the Green cone (deuteranomaly) vision, and severe loss of the Green cone (deuteranopia) vision. Coblis is available online at www.color-blindness.com/coblis-color-blindness-simulator/. Source: illustration created by Theresa-Marie Rhyne, 2015.

to be a mild disorder that does not affect daily living. Deuteranopia is the color deficiency with no working Green cone cells. For this case, Red appears as Brownish-Yellow and Green appears as Beige. Deuteranopia affects about 1% of males. Figure 2.13 depicts a Green cone color deficiency simulation created using the Coblis color blindness simulation tool.

Blue cone color deficiency simulation

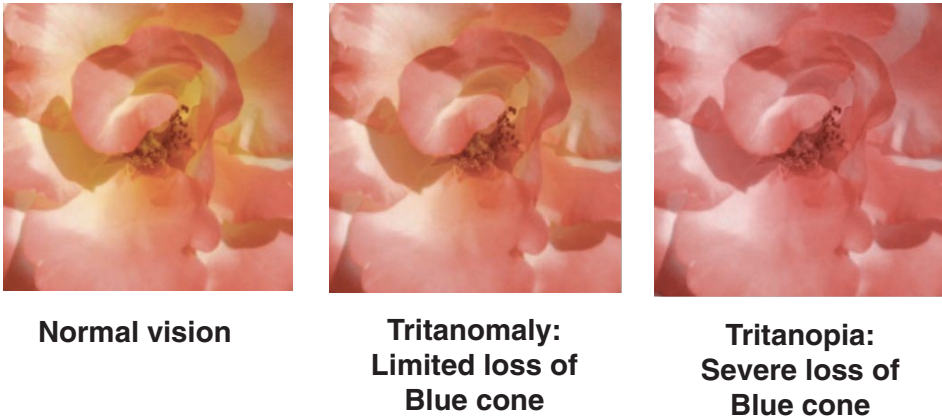


FIGURE 2.14 Blue cone color deficiency simulation: using the Coblis color blindness simulation tool, we depict an Orange and Yellow rose under normal vision, limited loss of the Blue cone (tritanomaly) vision, and severe loss of the Blue cone (tritanopia) vision. Coblis is available online at www.color-blindness.com/coblis-color-blindness-simulator/. Source: illustration created by Theresa-Marie Rhyne, 2015.

2.8.3 Blue Cone Color Deficiency

There are also Blue-Yellow color deficiencies where the Blue cone (tritan) photopigments either have limited function or are missing. Blue-Yellow color deficiencies occur less frequently than Red-Green color blindness and can affect males and females equally. With tritanomaly, the functionality of Blue cone cells is limited. Blue appears Greener, and it is challenging to differentiate Yellow and Red from Pink. This is an extremely rare color deficiency condition. Tritanopia is the color deficiency associated with a lack of Blue cone cells and is identified as Blue-Yellow color blindness. Blue appears as Green with Yellow appearing as Violet or Light Gray. Tritanopia is an extremely rare color deficiency affecting males and females. Figure 2.14 depicts a Blue cone color deficiency simulation created using the Coblis color blindness simulation tool.

2.8.4 Color Monochromacy and Rod Monochromacy

Additionally, there are two extraordinarily rare forms of color deficiency called color monochromacy and rod monochromacy. Color monochromacy is the result of two out of the three photopigments not functioning. As we discussed earlier, the brain needs to compare signals from different cones to produce color vision. So, individuals with Red monochromacy, Green monochromacy, or Blue monochromacy are challenged to distinguish color. Individuals with Blue monochromacy can have additional vision difficulties such as near-sightedness or visual acuity. Rod monochromacy, also called achromatopsia, is a severe form of color blindness where none of the cone cells have functioning pigments. This condition is present at birth and results in seeing the world in Black, White, and Gray tones. Individuals with rod monochromacy tend to be uncomfortable in bright

Monochromacy color deficiency simulation

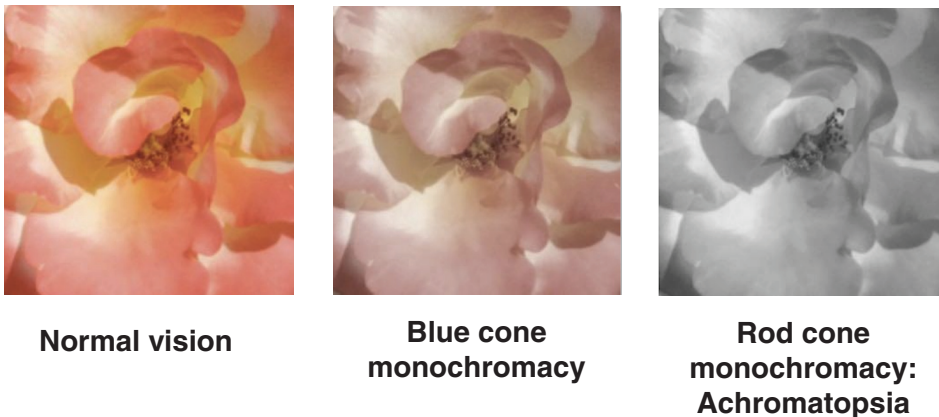


FIGURE 2.15 Monochromacy color deficiency simulation: using the Coblis color blindness simulation tool, we depict an Orange and Yellow rose under normal vision, Blue cone monochromacy vision, and Rod cone monochromacy or achromatopsia vision. Coblis is available online at www.color-blindness.com/coblis-color-blindness-simulator/. Source: illustration created by Theresa-Marie Rhyne, 2015.

environments since the rods in the eye respond to dim lighting. As noted earlier, color monochromacy and rod monochromacy are highly rare conditions in the human population. Figure 2.15 depicts a monochromacy cone color deficiency simulation created using the Coblis color blindness simulation tool.

2.9 SIMULATING AND DESIGNING FOR COLOR DEFICIENCIES

There are several online tools that aid in showing what images look like to individuals with color blindness. These simulation tools aid in designing digital media and visualizations to address color deficiencies. The Color Blindness Simulator (Coblis) is a freely available color blindness simulation tool. It allows for importing a jpeg image and viewing how that image appears under various color deficiency situations. We used Coblis to help us depict color deficiencies shown in Figures 2.12–2.15. The tool is available online at www.color-blindness.com/coblis-color-blindness-simulator. A jpg or jpeg is a frequently used compression format for digital images that was created in 1992. The acronym “jpeg” stands for the Joint Photographic Experts Group (JPEG) who created the digital image format. Detailed information on the jpeg digital image format is available at the JPEG website at www.jpeg.org/jpeg.

There are also color scheme suggestion tools that include a color blindness simulation function as part of their color scheme recommendation process. Adobe Color and Color Scheme Designer are examples of freely accessible online color scheme recommendation tools that have vision simulation functions. The vision simulations address the color deficiencies we outlined previously. Adobe Color is available at <https://color.adobe.com>. Color Scheme Designer is available from Paletton.com at <http://paletton.com>. ColorBrewer, a freely available online tool for color advice in cartography, includes a

color-blind safe icon for its suggested color schemes. The ColorBrewer tool is available at <http://colorbrewer2.org>. HCL Wizard (<https://hclwizard.org>) is another free color suggestion tool that has color vision simulations built into it. We will feature Adobe Color, Paletton's Color Scheme Designer, ColorBrewer and HCL Wizard in Chapter 6 of this book. We have only named a few of the color simulation and suggestion tools that include color vision simulation functions. There are many additional tools available for addressing color deficiency in the digital media and visualization design.

URLs for selected online software tools that address color deficiencies are as follows:

Coblis (www.color-blindness.com/coblis-color-blindness-simulator/)

Adobe Color (<https://color.adobe.com>)

Color Scheme Designer (<http://paletton.com/>)

ColorBrewer (<http://colorbrewer2.org>)

HCL Wizard (<https://hclwizard.org>)

2.10 AN EXAMPLE OF APPLYING COLOR DEFICIENCY STUDIES

In this example, we create a pie chart or color wheel that also represents the primary and secondary colors of the Red, Yellow, and Blue color model that we covered in Chapter 1. The primary colors are Red, Yellow, and Blue, while the secondary colors are Orange, Green, and Purple. We create a pie chart or color wheel with equal distributions of these colors in the clockwise order of Red, Orange, Yellow, Green, Blue, and Purple. These selected colors have similarities to the colors of Newton's rainbow diagram of Figure 1.3 and Newton's color circle of Figure 1.11 discussed in Chapter 1 of this book. Next, we use Coblis, as a color deficiency check, to assess how our color wheel jpeg image would look to individuals with protanopia, deutanopia, and tritanopia. We show our results in Figure 2.16.

From our color wheel example, in Figure 2.16, we can determine that people with Red-Green (protanopia) or Green-Red (deutanopia) deficiencies would not be able to easily tell the difference between the colors of Red, Orange, and Green. Additionally, the colors of Blue and Purple appear to have different shading values but do not appear as distinctively different colors for individuals with protanopia or deutanopia. For individuals with Blue-Yellow (tritanopia) deficiencies, the colors of Yellow, Orange, Red, and Purple appear to have different shading values but do not appear as distinctively different colors. Individuals with tritanopia also view Green and Blue to be different shades of each other rather than as distinctively different colors. So, if we apply this color mapping or color scheme to a data visualization problem, individuals with color deficiencies might not gain the intended insight during the visual analysis process.

2.11 PROBLEMS WITH THE RAINBOW COLOR MAP

Many visualization tools have used the *rainbow*, also called the *Newtonian*, color map as the default color palette in their visual analysis functions. As we show in Figure 2.17, the distances between Red, Orange, Yellow, Green, Blue, Indigo, and Purple colors are not

Red, Yellow, and Blue primary and secondary color wheel with color deficiency tests.

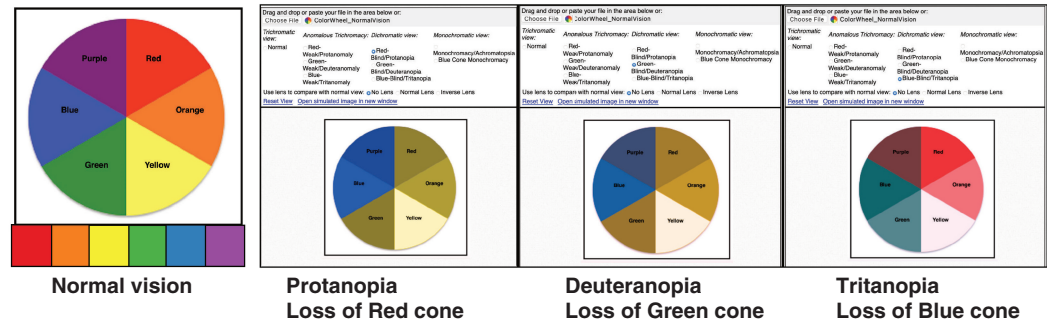


FIGURE 2.16 Example of applying color deficiency simulation analysis to the Red, Yellow, and Blue primary and secondary color wheel. Individuals with Red-Green (protanopia), Green-Red (deuteranopia), and Blue-Yellow (tritanopia) color deficiencies cannot differentiate the Red, Orange, Yellow, Green, Blue, and Purple colors that a person with normal color vision is able to detect. We used the Color Blindness Simulator (Coblis) tool for this analysis. Coblis is available online at www.color-blindness.com/coblis-color-blindness-simulator/. Source: illustration created by Theresa-Marie Rhyne, 2024.

Non-uniform distances between hues in rainbow color maps

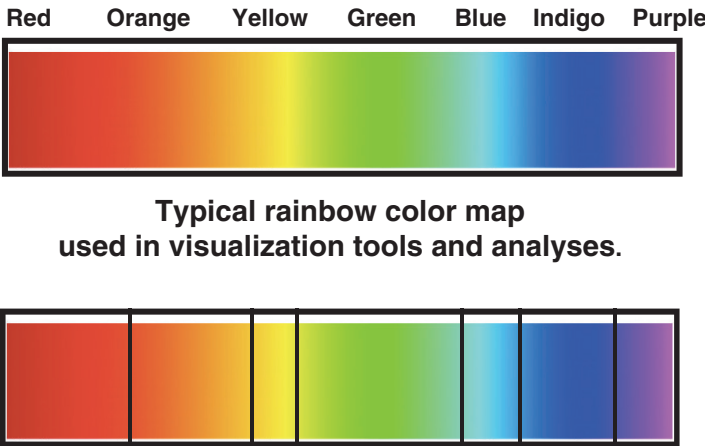


FIGURE 2.17 Non-uniform distances between hues in rainbow color maps. A traditional rainbow color map used in visualization and visual analytics software is shown here with the non-uniform distances between hues indicated. The distances between Red, Orange, Yellow, Green, Blue, Indigo, and Purple vary across the color spectrum. Using a rainbow color map to visualize data can produce perceptual errors in examining findings within the data set. Source: References [13,14] and illustration created by Theresa-Marie Rhyne, 2016.

perceptually uniform. When viewing data visualized with a rainbow color scheme, changes or transitions in data can be perceived incorrectly. Rogowitz and Treinish reported these concerns in their 1998 article on “Data Visualization: The End of the Rainbow”, while Borland and Taylor highlighted additional issues in a 2007 paper on “Rainbow Color Map (Still) Considered Harmful” [13,14]. Additionally, in 2011, Borkin and her team reported their findings from user studies on the application of various color maps, including the rainbow color map, to medical visualization problems [15]. Their research reported that a perceptually uniform color map resulted in fewer diagnostic errors than the rainbow color map. In 2019, Colin Ware and his team published a methodology for evaluating color map feature detection that highlights Newtonian color scheme difficulties [16]. In 2020, Crameri, Shephard, and Heron published a summary article entitled “The Misuse of Colour in Science Communication” that demonstrated the differences between using a non-uniform rainbow color scheme and using perceptually uniform color maps [17].

In Figure 2.18, we show non-perceptual uniform and perceptual uniform versions of a rainbow color scheme. This color scheme is not a Newtonian color map since Magenta is shown as the end color on the right. As we noted previously, Magenta is not a spectral color. We also note that neither Violet nor Purple is in this specific rainbow scheme. The features in the non-perceptual uniform example are a result of the design of the color map itself and can be confused as changes in data. The perceptual uniform color map removes these artifacts.

Several researchers have implemented perceptual uniform color map solutions in their visualization software. In 2009, Kenneth Moreland proposed a solution in his paper on “Diverging Color Maps for Scientific Visualization” that was incorporated into his

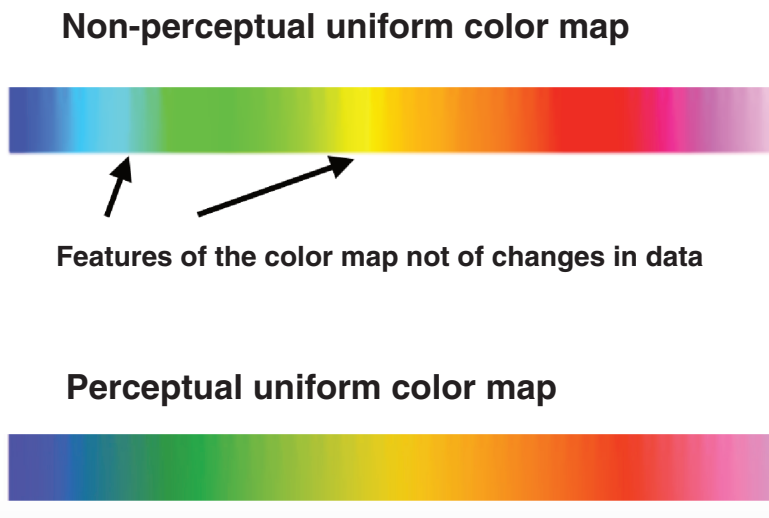


FIGURE 2.18 Non-perceptual uniform and perceptual uniform rainbow color maps. The features noted in the non-perceptual example are of the color map but can be confused as changes in data. The perceptual uniform color map smooths out and removes these artifacts. Source: illustration created by Theresa-Marie Rhyne, 2024.

“gencolormap” software and into the open-source large-scale visualization tool entitled “ParaView” [18]. In 2015, Nathaniel Smith and Stéfan van der Walt successfully proposed replacement color maps to the default Jet (rainbow) color scheme in Matplotlib that are now implemented [19]. In 2016, Moreland published two follow-up papers on “Why We Use Bad Color Maps and What You Can Do about It” that provide his practical advice on color map solutions beyond the rainbow color map [20,21]. After these and other solutions were implemented, many visualization researchers noted that a perceptual uniform rainbow color scheme has its merits. In 2021, Khairi Reda and Danielle Albers Szafr published “Rainbows Revisited: Modeling Effective Colormap Design for Graphical Inference” that reported cognitive advantages of rainbow color maps [22]. In 2023, Colin Ware, Maureen Stone, and Danielle Albers Szafr published their observations on this topic in “Rainbow Colormaps Are Not All Bad” [23]. The papers cited here are noted in the reference section at the end of this chapter.

2.12 CONCLUDING REMARKS

This chapter provided a general overview of color vision principles, including color deficiencies. Tools were introduced to help analyze how individuals with color deficiencies might view a digital image or visualization. How the use of a rainbow color map in visualizing data can produce perceptual errors in analyzing trends in the data was discussed. Chapter 3 examines color gamut, color spaces, and color systems and highlights the fundamentals behind the terminology used in online and mobile color specifications.

REFERENCES

1. Bruno, T.J. and Svoronos, P.D.N. (2005), *CRC Handbook of Fundamental Spectroscopic Correlation Charts*, Boca Raton, FL: CRC Press.
2. Wandell, B.A. (1995), *The Foundations of Vision*, Sunderland, MA: Sinauer Associates, <https://foundationsofvision.stanford.edu/>, accessed August 22, 2024.
3. Helmholtz, H.V. (1910), *Hermann von Helmholtz's Treatise on Physiological Optics*. Translated by the James P.C. Southall, 1924, New York: The Optical Society of America, Dover Publications, <https://catalog.hathitrust.org/Record/001555063>, accessed August 22, 2024.
4. Hering, E. (1878), *Outlines of a Theory of the Light Sense by Ewald Hering*. Translated by LM Hurvich and D Jameson, Cambridge, MA: Harvard University Press.
5. Hurvich, L.M. and Jameson, D. (1957), An opponent-process theory of color vision. *Psychological Review*, 64, 384–404.
6. Bowmaker, J.K. and Dartnall, H.J.A. (1980), Visual pigments of rods and cones in a human retina. *Journal of Physiology*, 298, 501–511.
7. Gouras, P. (2009), “Color Vision”, Webvision, University of Utah School of Medicine, <https://webvision.med.utah.edu/book/part-vii-color-vision/color-vision/>.
8. Schanda, J. (2007), *Colorimetry: Understanding the CIE System*, Hoboken, NJ: John Wiley & Sons.
9. Stone, M. (2003), Color vision, In: *A Field Guide to Digital Color*, pp. 43–64, Canada: A.K. Peters/CRC Press.
10. Neitz, J., et al. (2011), “Color vision”, *Adler's Physiology of the Eye*, 11th ed., LA Levin et al., eds., 648–654. New York, NY: Saunders.
11. Byrne, A. and Hilbert, D.R. (eds.) (1997), “Readings on color”, *Volume 2: The Science of Color*, Cambridge, MA: MIT Press.

12. Hilbert, D.R. and Byrne, A. (2010), “How do things look to the color-blind?”, *Color Ontology and Color Science*, J Cohen, M Matthen, eds., 259–290. Cambridge, MA: MIT Press.
13. Rogowitz, B.E. and Treinish, L.A. (1998), Data visualization: The end of the rainbow. *IEEE Spectrum*, 35 (12), 52–29.
14. Borland, D. and Taylor II, R.M. (2007), Rainbow color map (still) considered harmful. *IEEE Computer Graphics & Applications*, 27 (2), 14–17.
15. Borkin, M., Gajos, K., Peters, A., Mitsouras, D., Melchionna, S., Rybicki, F., Feldman, C., and Pfister, H. (2011), Evaluation of artery visualizations for heart disease diagnosis. *IEEE Transactions on Visualization and Computer Graphics*, 17 (12), 2479–2488.
16. Ware, C., Turton, T.L., Bujack, R., Samsel, F., Shrivastava, P., and Rogers, D.H. (2019), Measuring and modeling the feature detection threshold functions of colormaps. *IEEE Transactions on Visualization and Computer Graphics*, 25 (9), 2777–2790.
17. Crameri, F., Shephard, G.E., and Heron, P.L. (2020), The misuse of colour in science communication. *Nature Communications*, 11 (1), 1–10.
18. Moreland, K. (2009), “Diverging Color Maps for Scientific Visualization.” In *ISVC '09 Proceedings of the 5th International Symposium on Advances in Visual Computing: Part II*, 92–103, Berlin: Springer-Verlag.
19. Smith, N. and Van Der Walt, S. (2015), “mpl colormaps”, <https://bids.github.io/colormap/>, accessed on February 13, 2024.
20. Moreland, K. (2016), “Why We Use Bad Color Maps and What You Can Do About It”, *HVEI 2016 Proceedings of Human Vision and Electronic Imaging*.
21. Moreland, K. (2016), “Color Map Advice for Scientific Visualization”, <https://www.kenneth-moreland.com/color-advice/>, accessed February 13, 2024.
22. Reda, K. and Szafr, D.A. (2021), Rainbows revisited: Modeling effective colormap design for graphical inference. *IEEE Transactions on Visualization and Computer Graphics*, 27 (2), 1032–1042.
23. Ware, C., Stone, M., and Szafr, D.A. (2023), Rainbow colormaps are not all bad. *IEEE Computer Graphics and Applications*, 43 (3), 88–93.

Defining Color Gamut, Color Spaces, and Color Systems

3.1 COLOR GAMUT

Color gamut is a term used to describe the range of colors a device can reproduce. As indicated in Figure 2.1 of Chapter 2, the human eye–brain visual system can view a range of colors defined as the visible spectrum. Color imaging devices, such as digital cameras, mobile phones, scanners, monitors, and printers, have a smaller and narrower range of colors. Almost every device has a different color gamut. Color images on one device like your mobile phone will look different when printed from your inkjet printer due to the different range of colors reproducible on each of the respective devices. In Chapter 1, we highlighted the RGB display and CMYK printing color models, showing their complementary relationship in Figure 1.6. In general, the range of colors displayed on an RGB display device or a computer monitor is usually greater than the range of colors that can be produced by a CMYK printer. Converting digital media between devices alters the color gamut of the original source image with some colors becoming lost in the process. Figure 3.1 provides a comparison between RGB and CMYK color gamut ranges and demonstrates how RGB display colors transfer to CMYK printed colors.

In Chapter 2, we defined the luminosity or perceived brightness of a color. Figure 2.11 provides a comparison between RGB hues at full strength or the highest luminosity. Typically, Reds, Greens, and Blues with high luminosity on an RGB display device are not easily reproduced using only a CMYK ink or toner. Defining a color gamut for these respective systems helps us understand the variances in color ranges and determine optimal colors that will transfer effectively between devices. At this time, there are no devices that can reproduce the entire visible spectrum of human color vision. Working toward this unrealized goal has resulted in improved color display, scanning, and printing technologies.

How do we draw or diagram the color gamut of a device? A common method used is to work with the *x-y chromaticity diagram of the XYZ color space* established in 1931 by the

Comparison of RGB and CMYK color gamuts

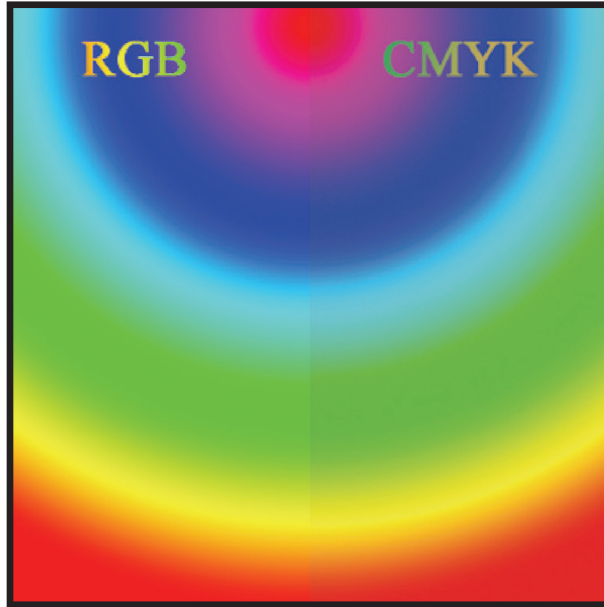


FIGURE 3.1 Comparison of RGB and CMYK color gamut ranges. This figure shows that the RGB color gamut differs from the CMYK color gamut. As a result, digital RGB images often appear altered when printed on a CMYK printer. Source: image originally created by Annette Shacklett in 2003 using Adobe Photoshop and in the public domain by request of the creator, https://commons.wikimedia.org/wiki/File:RGB_CMYK_4.jpg.

International Commission on Illumination (CIE). In Chapter 2, we defined chromaticity as an objective specification of the quality of a given color irrespective of the given color's luminance. Figure 3.2 shows the color gamut for a typical computer monitor. The Gray upside-down “U”-shaped region (often called a horseshoe) indicates the range of chromaticities visible to humans, based on the CIE 1931 chromaticity diagram. The colored triangle inside the *horseshoe* represents the color gamut available to some particular devices. The corners of the triangle show the primary colors of this gamut, with Red being the right point of the triangle, Green being the top point of the triangle, and Blue being the left point of the triangle. In Section 3.5 of this chapter, we describe the development of the CIE x-y chromaticity diagram in further detail. This is the Grayed-out portion of Figure 3.2, including the rainbow color triangle. For a general overview of color gamut and color models, we refer you to Reference [1] by Ibraheem et al., noted at the end of this chapter.

3.2 COLOR SPACES

Figure 3.2 also shows the color space of our typical computer monitor. For this situation, our color space is the combination of the RGB color model and the color gamut of the given typical computer monitor. This relationship is summarized as follows: RGB color

**Color gamut of a typical computer monitor
(displayed in the CIE 1931 chromaticity diagram format)**

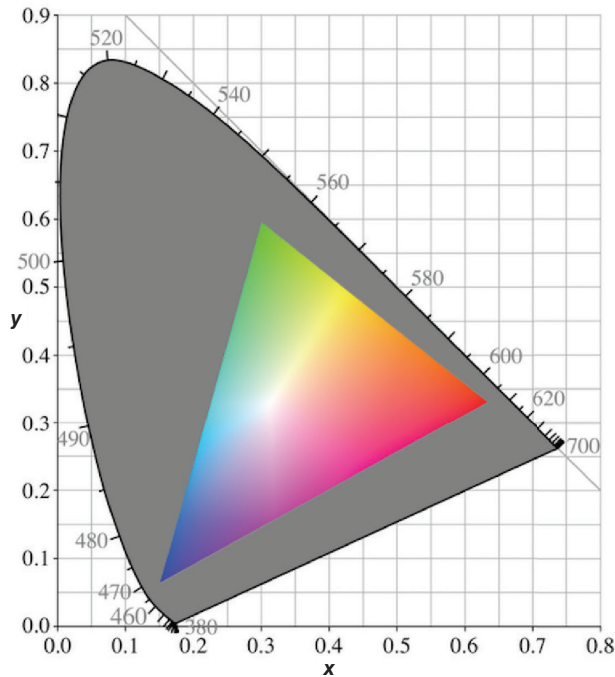


FIGURE 3.2 Color gamut of a typical computer monitor. The Gray upside-down U or horseshoe shape represents the entire range of colors in the visible spectrum or chromaticity values based on the CIE 1931 XYZ color space. Source: image originally created by Hankwang and Aboalbliss in 2006 using Adobe Photoshop and in the public domain by request of the creators, https://commons.wikimedia.org/wiki/File:CIExy1931_srgb_gamut.png.

model + color gamut = color space. A color space can be an arbitrary color system or a mathematically structured system. The *Pantone matching system* is an example of an arbitrary color system based on color swatches and corresponding assigned names. We will discuss the Pantone matching system later in this chapter. As we noted in Chapter 2, a color model with a mathematical structure can be represented as tuples of numbers. For the RGB color model, three numbers represent the Red, Green, and Blue values as we showed for Yellow (255, 255, 000) in Figure 2.9. There are several specific color spaces that are based on the RGB color model. A complete specification of an RGB color space also includes a White point chromaticity value and a *gamma correction curve* (refer to Ibraheem et al. [1] and Schanda [2] for further details on complete specifications of the RGB color space as this is beyond the scope of our efforts). In Figure 3.2, we see a White point inside the triangle where the colors converge. Susstrunk, Buckely, and Swen in their 1999 paper on “Standard RGB Color Spaces” describe the specifications and usage of standard RGB color spaces. For a more detailed discussion of the derivation and mathematical structure of RGB color spaces, we refer you to their paper, noted as Reference [3] at the end of this chapter.

3.3 COMMONLY APPLIED RGB COLOR SPACES

The most commonly applied RGB color spaces in digital media and visualization are sRGB, Adobe RGB, and ProPhoto RGB. Hewlett-Packard Company and Microsoft Corporation cooperatively created and then proposed sRGB as a standard, in 1996, to approximate the color gamut of the most common computer display devices. Since sRGB effectively serves as a best guess for how the majority of monitors, mobile phones, and digital cameras produce color, it has become the standard color space for displaying images on the Internet. As a result, many software applications and Web specifications are designed around the sRGB specification. The sRGB color gamut includes approximately 35% of visible colors specified in the 1931 CIE chromaticity diagram.

Adobe RGB was developed and published in 1998 by Adobe Systems Inc. to encompass the majority of colors supported by CMYK printers by using only RGB primary colors on display devices. The Adobe RGB color space is targeted at providing fewer challenges in transferring colors from RGB displays to CMYK printing output devices. The Adobe RGB color gamut includes approximately 50% of visible colors specified in the 1931 CIE chromaticity diagram. Adobe RGB supports richer Cyan and Green hues than sRGB.

Kodak began development on ProPhoto RGB in the late 1990s with the specification becoming available in the early 2000s. The intent was to offer a very large gamut, beyond that available with sRGB, designed for use with a photographic output. ProPhoto RGB encompasses about 79% of the colors specified in the 1931 chromaticity diagram. The recognized downside of ProPhoto RGB is that approximately 13% of the colors in the ProPhoto RGB color space do not exist and are thus “imaginary” colors. As a result, converting a ProPhoto RGB image to sRGB, Adobe RGB, or CMYK formats can result in unexpected and undesired colors. Many digital photographers prefer to work in ProPhoto RGB in order to preserve the color gamut of their original digital images. Figure 3.3 shows the color gamut map of the color spaces we have described here. The 2200 Matt Paper notation in Figure 3.3 refers to the CMYK color space of an Epson 220 color inkjet printer. References [4,5] provide more details about these commonly applied RGB color spaces.

3.4 COLORIMETRY

The science of color measurement and matching is called *colorimetry*. As we discussed in our definition of metamerism in Section 2.5 of Chapter 2, when we observe a colored object, our visual system has no way of knowing from its appearance the spectral composition of the physical stimulus. Our brain does not distinguish a Yellow light from an equal combination of Red and Green lights with zero Blue lights. Colorimetry provides a system of color measurement and specification based upon the concept of equivalent-appearing stimuli. Colorimetry data is gathered from empirical studies of humans matching colors. The task of each human subject is to use the three primary lights of Red, Green, and Blue (RGB) to match a designated “reference” color. When a match is established, the reference color can then be defined in terms of the amount of the respective Red, Green, and Blue lights required to produce the equivalent reference color. The observer is developing a set of *tristimulus* values. Figure 3.4 provides a schematic diagram of colorimetry color matching by observers.

Gamut map of commonly applied RGB color spaces

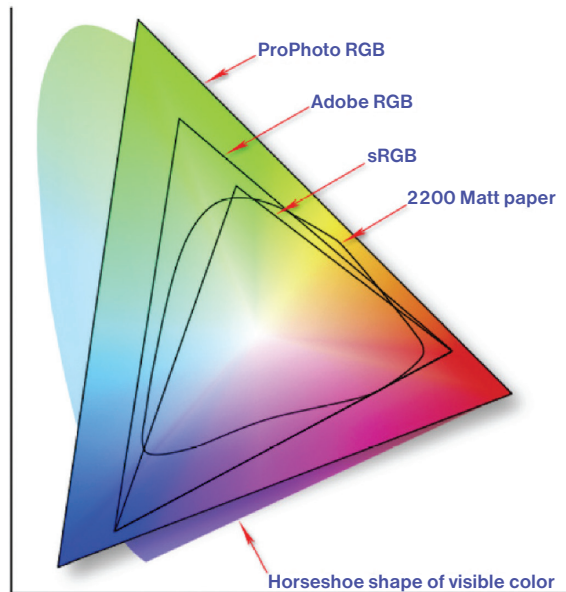


FIGURE 3.3 Gamut map of commonly applied RGB color spaces. This figure compares the sRGB, Adobe RGB, and ProPhoto RGB color spaces using the entire range of colors in the visible spectrum or chromaticity values based on the CIE 1931 XYZ color space. The CMYK color space is also depicted as 2200 Matt Paper or the printed output from an Epson 2200 color inkjet printer. ProPhoto RGB covers the largest range (about 79%) but also includes “imaginary” colors that cannot be reproduced. Adobe RGB covers the second largest (about 50%) range, while sRGB covers the smallest range (about 30%). Additionally, there are colors that can be printed in the CMYK color space that are outside both the sRGB and Adobe RGB color spaces. Source: image created by Jeff Schewe in May 2007 and in the public domain by request of the creator, <https://commons.wikimedia.org/wiki/File:Colorspace.png>.

With colorimetry work, there is the challenge of how to handle reference colors that cannot be matched. The practice developed is to apply a “negative light”. If the blend of RGB lights is too Reddish for color matching even though no Red light is shining, the human subject is permitted to shine some of the Red primary light on the reference color to make the desired match. These results are recorded. Using this approach, it is possible to match all remaining colors with any set of the RGB distinct colors assuming the use of the “negative light” as noted above. Figure 3.5 depicts the color matching functions used in colorimetry tests associated with the CIE 1931 RGB color space.

We will further discuss these concepts in the next section on the CIE XYZ and xyY color spaces. A robust multi-authored publication on colorimetry entitled *Colorimetry: Understanding the CIE System* was edited by Janos Schanda in 2007 [2]. Maureen Stone provides a more generic but a detailed overview of colorimetry experiments in the first chapter (Color Vision) of her 2003 book titled *A Field Guide to Digital Color* [6].

3.5 THE CIE XYZ COLOR SPACE AND THE CIE X-Y CHROMATICITY DIAGRAM

The International Commission on Illumination (or *Commission Internationale de l'Éclairage*, CIE) was founded in 1913 to serve as an autonomous international board for the exchange of information and to set standards on items related to lighting. As part of this mission, the CIE has a technical committee entitled “Vision and Colour” that has served as a leading force in colorimetry since its first meeting to set standards in 1931. The CIE 1931 color space was developed to be independent of devices or other means of emission or reproduction of color. The standard was based on colorimetry experiments, conducted by William David Wright and John Guild in the 1920s, about how humans perceive color. Wright published his results in 1929, while Guild, independently, published his results in 1931. As Figure 3.4 shows, the human subjects (or observers) in these colorimetry experiments developed tristimulus values by visually matching a test color against the Red, Green, and Blue (RGB) primary colors. Figure 3.5 shows the color matching functions used in developing the CIE RGB color space. Due to the distribution of cones in our eyes, tristimulus values are dependent on an observer’s field of view. The CIE established a color mapping function called *the standard (colorimetric) observer* to remove this variable. The *CIE 1931 Standard Observer* (also called the CIE 1931 2° Standard Observer) is based on the assumption that color-sensitive cones are located within two degrees (2°) of the arc of the fovea inside the retina of the eye. As stated in Section 2.2 of Chapter 2, the fovea is at the center of the retina in our eyes.

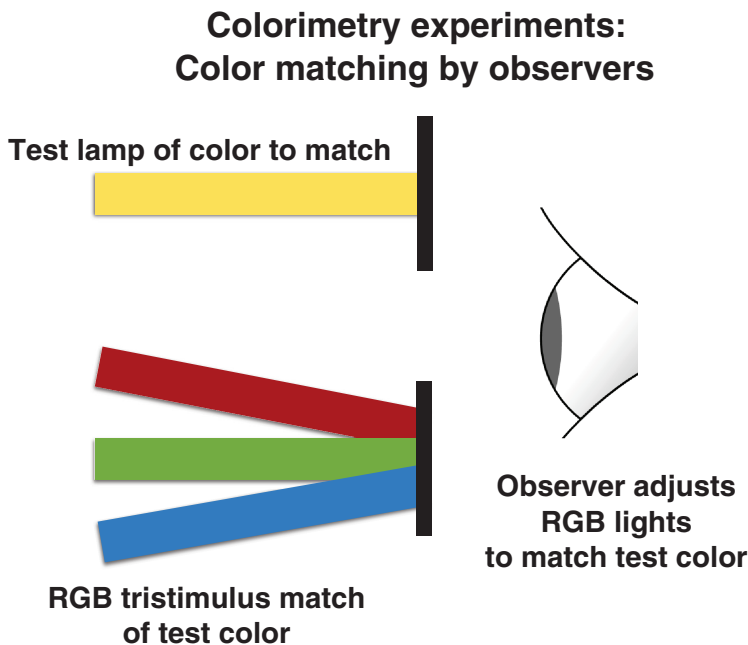


FIGURE 3.4 Diagram of a colorimetry experiment where an observer adjusts a set of Red, Green, and Blue (RGB) lights to match a test lamp of color. Source: illustration by Theresa-Marie Rhyne, 2015.

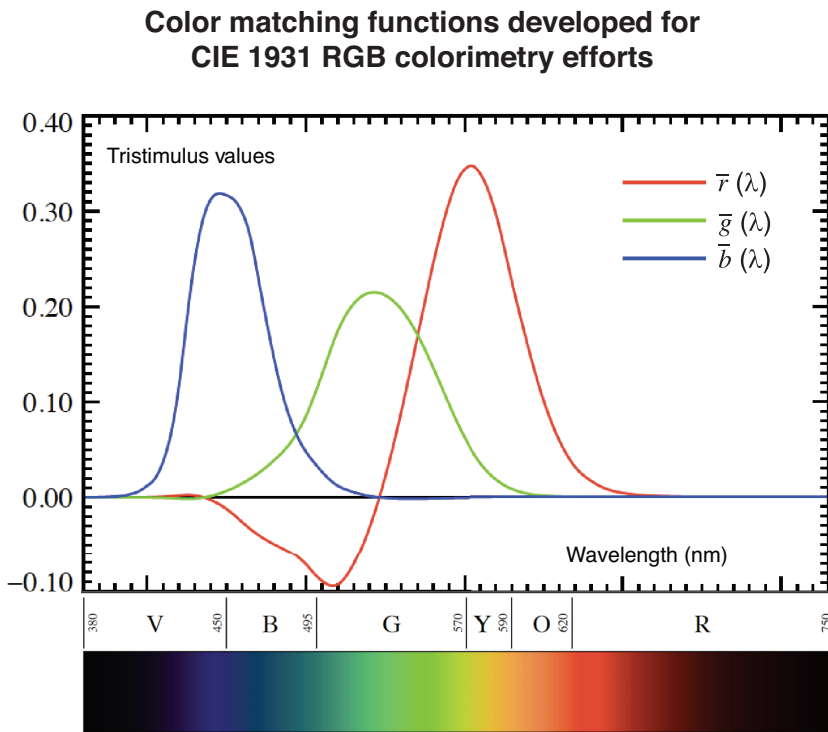


FIGURE 3.5 Color matching functions developed for CIE 1931 RGB colorimetry efforts. Source: diagram created by Marco Polo in November 2007 and in the public domain by request of the creator, https://commons.wikimedia.org/wiki/File:CIE1931_RGBCMF.svg. Color spectrum image created by Gringer in 2008 and in the public domain by request of the creator, https://commons.wikimedia.org/wiki/File:Linear_visible_spectrum.svg.

The CIE considered the use of direct RGB data from the human subject colorimetry studies to be undesirable for establishing a standardized color space. This concern pertained to study results that permitted negative RGB values as shown in Figure 3.5. Instead, a mathematical formula was developed to convert the RGB data to a system of only positive integers. These reformulated values were noted as XYZ. The resulting XYZ numbers approximate but do not directly correspond to the Red, Green, and Blue values of the Wright and Guild colorimetry studies. Figure 3.6 depicts the resulting CIE XYZ tristimulus values that are also called the CIE Standard Observer matching functions.

The CIE also derived a two-dimensional equivalent to the CIE XYZ color space called the *CIE x-y chromaticity diagram*. This is the horseshoe-shaped diagram we have discussed in Sections 3.1 and 3.3. The CIE established a new set of chromaticity coordinates called x , y , and z exhibiting the property that $x+y+z=1$. The coordinate z is not displayed in the CIE x - y chromaticity diagram but can be derived from the $x+y+z=1$ relationship. The two-dimensional visualization is a result from developing a chart with x and y as its axes to plot points that indicate chromaticity. In working in the CIE XYZ color space, the tristimulus values are always indicated in upper case as X , Y , and Z and the chromaticity

CIE 1931 XYZ standard observer color matching functions

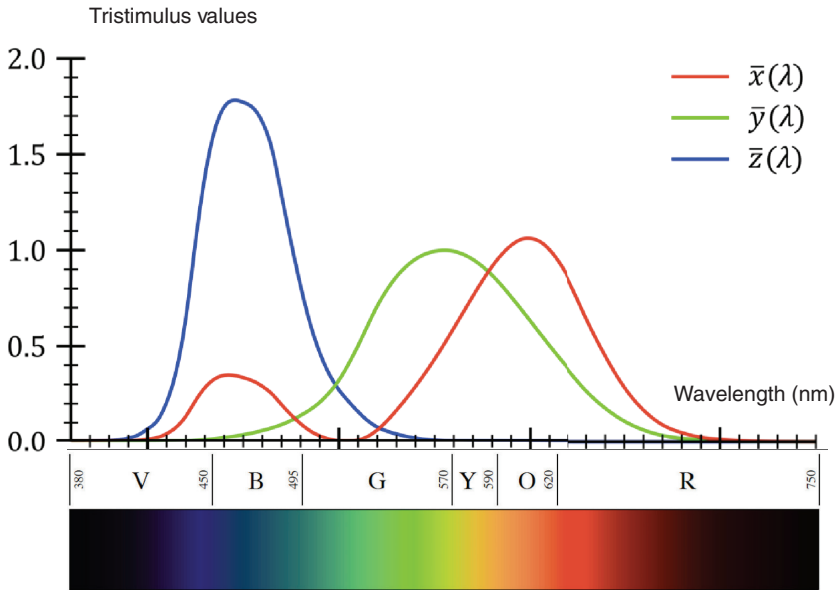


FIGURE 3.6 Diagram of the CIE Standard Observer functions that resulted from converting the original CIE RGB data (shown in Figure 2.10) into the CIE XYZ system of only positive integers. Source: plot created by Acdx in March 2009 and copied, distributed, and modified under the GNU Free Documentation License, https://commons.wikimedia.org/wiki/File:CIE_1931_XYZ_Color_Matching_Functions.svg. Color spectrum image created by Gringer in 2008 and in the public domain by request of the creator, https://commons.wikimedia.org/wiki/File:Linear_visible_spectrum.svg.

coordinates are always noted in lower case as x , y , and z . We show this visualization of the CIE x - y chromaticity diagram in Figure 3.7.

Plotting the x and y values of spectral colors ranging from 400 to 700 nm on the x - y chromaticity diagram results in a horseshoe-shaped curve that we introduced in Section 3.1. The edge line of this horseshoe-shaped diagram is called “*the spectral locus*”. The spectral locus represents a pure monochromatic light measured by the wavelength in nanometers. These are the most saturated colors of the horseshoe. Notice the correspondence between the spectral locus values in Figure 3.7 with the visible light spectrum in Figure 2.1. The non-spectral Magenta or Purple-Red mixtures fall along the straight line joining the 400-nm point to the 700-nm point of the horseshoe. This line is often termed the “*Line of Purples*”. The colors of the Line of Purples are also fully saturated and are made by mixing Red and Blue colors. All visible colors fall within the resulting closed horseshoe curve. Pale and unsaturated colors lie nearer the center of the diagram. The central point of $x = 1/3$ and $y = 1/3$ is defined as the achromatic point where visually perceived “White” is located. If we define two colors in the chromaticity diagram as individual end points and place a line

CIE x-y chromaticity diagram

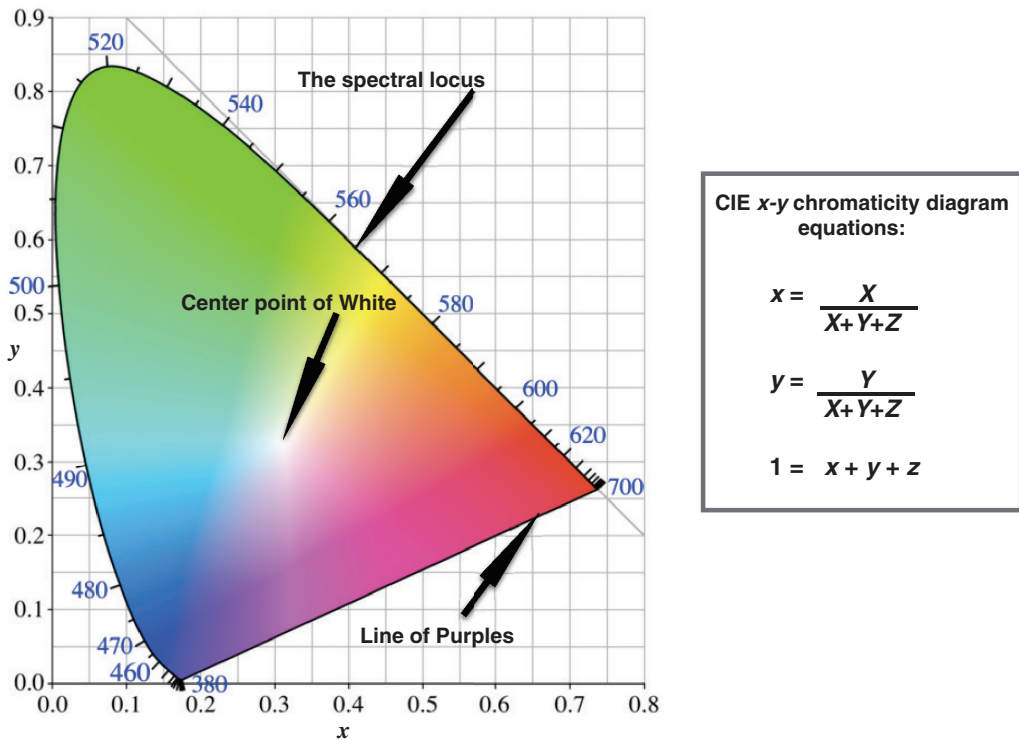


FIGURE 3.7 CIE x - y chromaticity diagram that results from the CIE XYZ color space tristimulus value being converted into chromaticity coordinates of x , y , and z according to the equations noted. The z values do not appear but can be calculated due to the $1 = x + y + z$ equation. All visible colors fall within the closed horseshoe-shaped curve. The “spectral locus” edge line of the horseshoe represents pure spectral colors ranging from 400 to 700 nm. The “Line of Purples” or the bottom line of the horseshoe shape represents the non-spectral Magenta and Purple-Red mixtures created by mixing Blue and Red. The central point of $x = 1/3$ and $y = 1/3$ defines the achromatic point where visually perceived “White” is located. Source: image created by PAR in June 2005 and in the public domain by request of the creator, <https://en.wikipedia.org/wiki/File:CIExy1931.png#/media/File:CIExy1931.png>. Text Annotations and additions of equations provided by T-M Rhyne, 2015.

between them, the colors along the resulting line are produced via combinations of the two color end points. The Line of Purples is one demonstration of this characteristic.

There are many principles and mathematical functions that were established in developing the CIE XYZ color space and the CIE x - y chromaticity diagram. In 1997, Fairman, Brill, and Hemmendinger published their paper on “How the CIE 1931 color-matching functions were derived from Wright-Guild data” [7] that provides one of the more detailed discussions on this topic. In 2007, the reflections and perspectives of William David Wright were published in a discussion entitled “Professor Wright’s Paper from the Golden Jubilee Book: The Historical and Experimental Background to the 1931 CIE System of Colorimetry” [8] in *Colorimetry: Understanding the CIE System* edited by Janos Schanda.

We refer you to these papers for further discussion on the development of the CIE 1931 system for colorimetry. One of the shortcomings of the CIE x - y chromaticity diagram is that colors of equal amounts of difference appear further apart in the Green region of the visualization than they do in the Red or Violet part. It is frequently noted that Green takes up a disproportionately large fraction of the horseshoe shape compared to the other colors. To address this issue of non-uniform scaling, the CIE adopted two uniform diagrams, CIE LUV and CIE LAB, as specifications in 1976. We will highlight CIE LUV and CIE LAB in the next sections of this chapter. Despite this problem of non-uniform scaling, the CIE x - y chromaticity visualization remains the most common chromaticity diagram in use.

3.6 CIE LUV AND CIE LAB

In 1942, David Lewis MacAdam published research in the *Journal of the Optical Society of America* [9] that noted the non-uniform scaling of the CIE x - y chromaticity visualization. This research showed that the physical distance of two colors on the CIE x - y chromaticity diagram may not be equivalent to their perceptual “distance”. To correct this limitation, a number of uniform chromaticity scale (UCS) solutions were proposed. The UCS solutions used mathematical relationships to transform the XYZ values or the x and y coordinates to a new set of values that created a more nearly perceptually uniform two-dimensional color space. Additionally, the Y lightness scale was replaced with a new scale called L^* that was approximately uniformly spaced and more indicative of actual visual differences. In 1976, the CIE adopted two color spaces that more effectively showed uniform color spacing in their values. These are CIE LUV and CIE LAB with the L^* lightness scale being used in both of these color spaces. The CIE LUV color space was designed specifically for emissive colors that correspond to images captured by a camera or created by computer graphics rendering programs. As a result, CIE LUV is used in the display industry. The CIE LAB color space was developed to characterize color surfaces and dyes. CIE LAB is used widely in the color imaging and printing industries. We highlight aspects of CIE LUV and CIE LAB below.

For the mathematical relationships of UCS solutions and further technical information on CIE LUV and CIE LAB, we refer you to the *Digital Color Imaging Handbook*, edited by Gaurav Sharma and Raja Bala [10,11].

3.6.1 CIE LUV

As noted earlier, CIE LUV is a transformation of the CIE XYZ color that represents an attempt to achieve a greater correspondence between physical distance on the graph and perceptual uniformity. CIE LUV is widely used in computer graphics applications. In 1960, the CIE adopted a 1960 chromaticity diagram to address the non-uniform scaling called the 1960 CIE u, v chromaticity diagram. However, the u, v approach was found to be perceptually unsatisfactory. As a consequence, in 1975, the CIE proposed new u' and v' values. The new scaling became $u' = u$ and $v' = 1.5v''$. The new scaling thus became $u' = u$ and $v' = 1.5v$. The revised diagram was adopted as the 1976 CIE $u' v'$ diagram (for further details, see Reference [11]). Figure 3.8 shows the 1976 CIE $u' v'$ chromaticity diagram with the transformation equations.

CIE u'v' chromaticity diagram

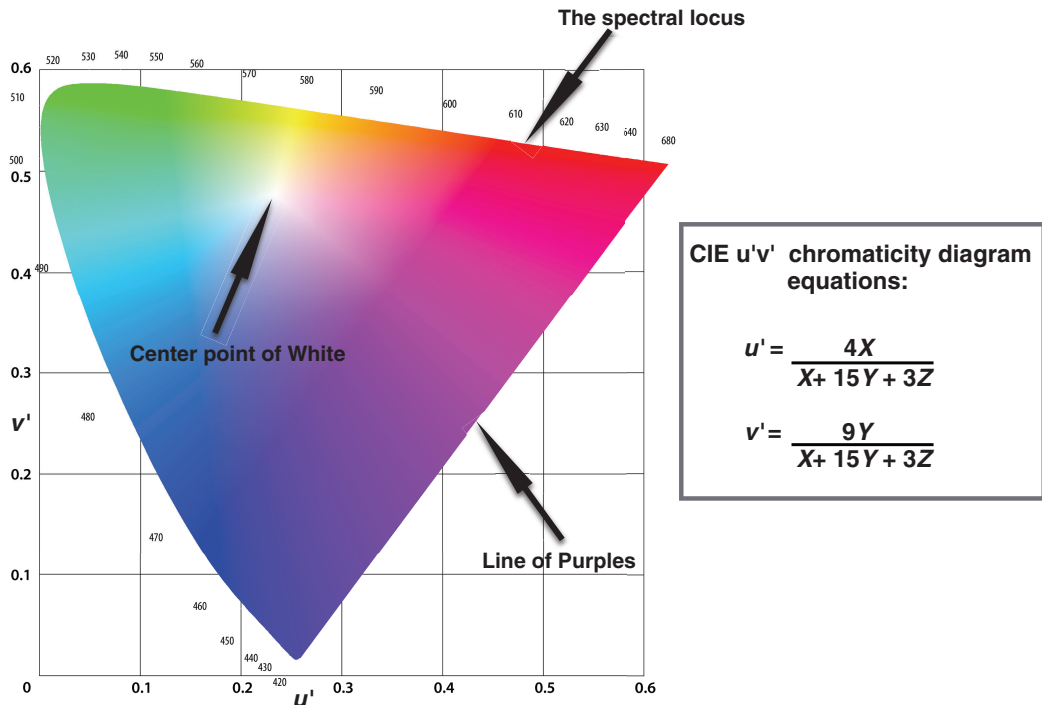


FIGURE 3.8 1976 CIE $u' v'$ chromaticity diagram associated with the CIE LUV color space. CIE LUV transforms the 1931 CIE XYZ color space to attempt perceptual uniformity. After the development of 1931 CIE $x-y$ chromaticity diagram, it was shown that colors equally distant on the 1931 CIE $x-y$ chromaticity diagram were not necessarily equally distant perceptually. The 1976 CIE $u' v'$ chromaticity diagram is an endorsed effort to correct this. The 1976 CIE LUV color space is used extensively in computer graphics applications. Source: image created by Adonisick in March 2008 and in the public domain by request of the creator, https://en.wikipedia.org/wiki/CIELUV#/media/File:CIE_1976_UCS.png. Text Annotations and additions of equations provided by T-M Rhyne, 2015.

The development of UCS solutions to address perceptual uniformity alters the resulting CIE chromaticity visualization. As a result, the Blue-Red portions are elongated and the achromatic White point is relocated in order to ensure a greater correspondence between physical and perceptual distances. The spectral locus is shortened, and the Line of Purples is also altered. Figure 3.8 shows these changes that result in the 1976 CIE $u' v'$ chromaticity diagram [12,13].

3.6.2 CIE LAB

CIE LAB is the second of the two systems that the CIE adopted in 1976 to address perceptual uniformity. CIE LAB is a *three-dimensional opponent* color space that accurately represents perceptual distances between different colors. As we covered in Section 2.4 of

Chapter 2, Ewald Hering developed the opponent color theory concept in 1878. Opponent theory explains aspects of color vision processing at the neural level when images are transferred from the eye to the brain via the optic nerve. In the brain, retinal color stimuli become translated into distinctions between: (1) light and dark (White to Black); (2) Red and Green; and (3) Yellow and Blue. CIE LAB indicates these three components where a first axis (L^*) plots the lightness or luminance from White to Black, a second axis (a^*) plots values between Red and Green, and a third axis (b^*) plots values between Yellow and Blue. These color axes are determined by the concept that a given color cannot simultaneously be Red and Green, or Yellow and Blue, because these colors are in opposition. On the a^* axis, positive values represent amounts of Red, while negative values represent amounts of Green. On the b^* axis, positive values represent amounts of Yellow, while negative values represent amounts of Blue. Individual colors are referenced according to their corresponding positions on all three axes. Figure 3.9 shows our three-dimensional representation of the CIE $L^*a^*b^*$ color space.

CIE $L^*a^*b^*$ is a device-independent color space that includes all perceivable colors, and its gamut exceeds those of the RGB and CMYK color models. This allows CIE $L^*a^*b^*$ to serve as an intermediary color space where values from a particular gamut are re-encoded as CIE $L^*a^*b^*$ values and other devices can convert the resulting CIE $L^*a^*b^*$ values into

Representation of CIE $L^*a^*b^*$ opponent color space

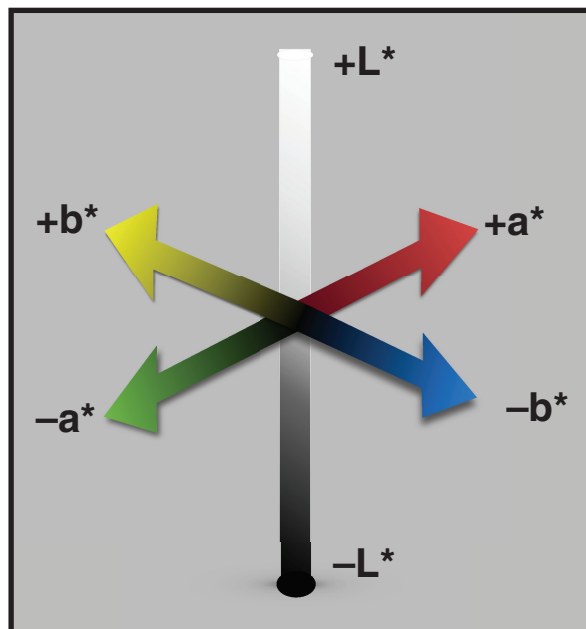


FIGURE 3.9 Three-dimensional representations of the components of the 1976 CIE LAB color space. Source: illustration by Theresa-Marie Rhyne, 2015.

their own specific color gamut. CIE $L^*a^*b^*$ is a useful framework for linking digital media to color printing technology and provides a color space for painters to better understand the challenges of mixing differently colored pigments. Many color evaluation tools refer to CIE LAB as “Lab”. As we begin to discuss online and mobile tools for color analysis and suggestion, please note that Lab refers to CIE LAB.

The CIE LAB color space is based on efforts that date back to the 1940s. In 1942, Elliott Quincy Adams published “X-Z planes in the 1931 I.C.I. system of colorimetry”, which describes two color spaces that were precursors to the 1976 CIE LAB and CIE LUV color spaces [14]. In 1944, Dorothy Nickerson and her assistant, K.F. Stultz, built upon Adams work to develop a color difference formula that in a modified form would eventually become the CIE LAB color space and difference formula [15]. This color difference relationship became known as the Adams–Nickerson–Stultz formula. The 1943 “renotations” and other fundamental aspects of the Munsell color system, covered in Section 3.8, were reviewed as a part of the process of developing the 1976 CIE LAB specification.

Also in the late 1940s, Richard Hunter independently began work on the Hunter Lab color space that evolved through the 1950s and 1960s. In 1966, Hunter released his formulas for converting CIE XYZ values to the Hunter L, a, b coordinates as the Hunter Lab Application Notes [16,17]. The Hunter Lab color space was also a precursor to CIE LAB. The 2012 Hunter Lab Application Note highlights some of the differences between the Hunter L, a, b and CIE L^*, a^*, b^* [18].

The CIE LAB specification resulted from fusing these prior contributions. The (*) representations denote mathematical transformations that resulted in creating the final CIE $L^*a^*b^*$ color space. As we have noted previously under the 3.6.1 CIE LUV discussion, “Color fundamentals for digital imaging” in the *Digital Color Imaging Handbook* is an excellent reference for understanding the mathematical transformations and relationships of CIE color spaces, including CIE $L^*a^*b^*$ [10].

3.7 COLOR APPEARANCE MODELS

Colorimetry is focused on examining whether colors appear to match under a defined set of viewing conditions. Our eyes receive color under a variety of viewing conditions beyond these XYZ tristimulus values. A color appearance model (CAM) provides mathematical or numerical descriptions of how the appearance of colors changes in different viewing situations. For example, the colors we select on our mobile phones might appear very different in a large display environment.

The CIE LUV and CIE LAB uniform color spaces were tentative numerical steps to model hue, lightness, chroma, and saturation to address color appearance. Researchers in the 1980s and 1990s began to develop CAM systems beyond these initial efforts. In 1997, CIECAM97s was successfully introduced as an interim comprehensive model but was difficult to use [19]. CIECAM02, after academic and industry assessments, was released in 2002 [20]. CAM16 was a 2016 successor of CIECAM02 with various fixes and improvements [21]. In 2020, a uniform color space that combined the similar structure of CIE LAB with improved CAM16 data was introduced as Oklab [22]. As of 2023, Oklab gained acceptance and is supported in Web browsers [23].

In future sections of this chapter, we will discuss various color spaces and standards that address hue, lightness, chroma, and saturation. These include the Munsell color system, the hue, chroma, and luminance (HCL) color space, hue, saturation, and value (HSV), hue, saturation, and lightness (HSL), and the World Wide Web Consortium color specifications. It is beyond this book to provide an in-depth treatment of color appearance models. For these types of discussions, we refer you to Mark D. Fairchild's book on *Color Appearance Models*, 3rd Edition. Fairchild is a leading researcher in color who pioneered the development of CIECAM02 and made additional color appearance contributions.

3.8 THE MUNSELL COLOR SYSTEM

The *Munsell color system* is a three-dimensional model that defines color as having three attributes: hue, value, and chroma [24]. Albert H. Munsell, an American artist and art educator, developed the color order system in the 1890s to establish a notation of color with systematic order that obviated the need for what he called “misleading” color names. The system is built on the representation of equally perceived color differences as a branching geometry called a *color tree*. The Munsell color order system has served as the basis for a variety of government and industry specifications. These include the US Department of Agriculture's soil conservation and food industry specifications, the American National Standards Institute's color specifications, the National Electrical Manufacturers Association color specifications, and many more. The Munsell color system is also fundamental to many color specifications that followed it such as CIE LAB. The Munsell color system remains as one of the more popular and internationally used color order systems to this day. It is recognized by the American National Standards Institute (ANSI z138.2), the Japanese Industrial Standard for Color (JIS Z872), and the German Standard Color System (DIN 6161), and it serves as a basis for several British national standards. Because of its influence, we discuss it in greater detail below.

3.8.1 Evolution of the Munsell Color Order System

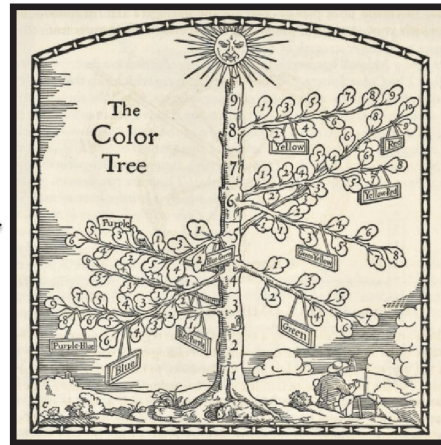
Munsell initially conceived of a color sphere as the basis for his system. In 1898, he began a study of the color sensitivities of the human visual system using experimental tools of his own devising. From these observations, Munsell came to the conclusion that color space is not naturally geometrically regular. Munsell abandoned the color sphere concept and proposed a three-dimensional color tree model for his color system. The uneven color tree branches are based on equally perceived color differences. Figure 3.10 shows the evolution of Munsell's model for his color order system from a three-dimensional color sphere to a three-dimensional color tree.

In 1905, in his book, entitled *A Color Notation*, Munsell described his color theory. In 1915, the *Atlas of the Munsell Color System* book provided 15 charts that illustrated colored specimens for a range of values and chromas of the 10 fundamental hues of the color system. In 1921, after Munsell's death in 1918, *A Grammar of Color: Arrangements of Strathmore Papers in a Variety of Printed Color Combinations According to the Munsell Color System* was published that included an introduction by Munsell along with the explanatory text and diagrams applying the system prepared by Thomas Maitland (T.M.) Cleland [25–27].

Evolution of the Munsell color framework: From Color Sphere to Color Tree



The Color Sphere: initially proposed in Munsell's 1905 "Color Notation" publication.



The Color Tree: as it appeared in the Munsell & Celand 1921 "Grammar of Color" publication.

FIGURE 3.10 Evolution of the Munsell framework. Illustration combines elements from Reference [25], plate 1; and Reference [27], public domain.

In 1917, shortly before his death, Munsell founded the Munsell Color Company as a business vehicle for producing color standards. After Munsell's death, his son, Alexander Ector Orr Munsell, built on the elder Munsell's work. The 1929 edition of *The Munsell Book of Color*, with its improved color scales, displayed 20 hues. In 1943, using the CIE 1931 Standard Observer functions (discussed in Section 3.4 of this chapter), a subcommittee of the Optical Society of America recommended "renotations" to the Munsell color system. These renotations were adopted and provided a convenient method for converting standardized color measurement data to the Munsell color system. Additional revisions resulted in the adoption of the Munsell color system as a basis for colorimetry specifications used by those US government agencies previously mentioned. In the early 1950s, the number of hues in *The Munsell Book of Color* expanded from 20 to 40 hues. Improvements to the Munsell color order system have evolved over time. For further reading on the history of the Munsell color system, we refer you to Dorothy Nickerson's 1976 three-part discussion on system's history [28–30]. The company continues today as a part of X-Rite, Inc., a manufacturer of color measurement and color management solutions (see www.munsell.com). More information on the latest versions of *The Munsell Book of Color* is available on this website. Figure 3.11 provides a combined illustration of the hue, value, and chroma attributes of the Munsell color system from the 1921 book.

Munsell color system: Hue, value and chroma attributes

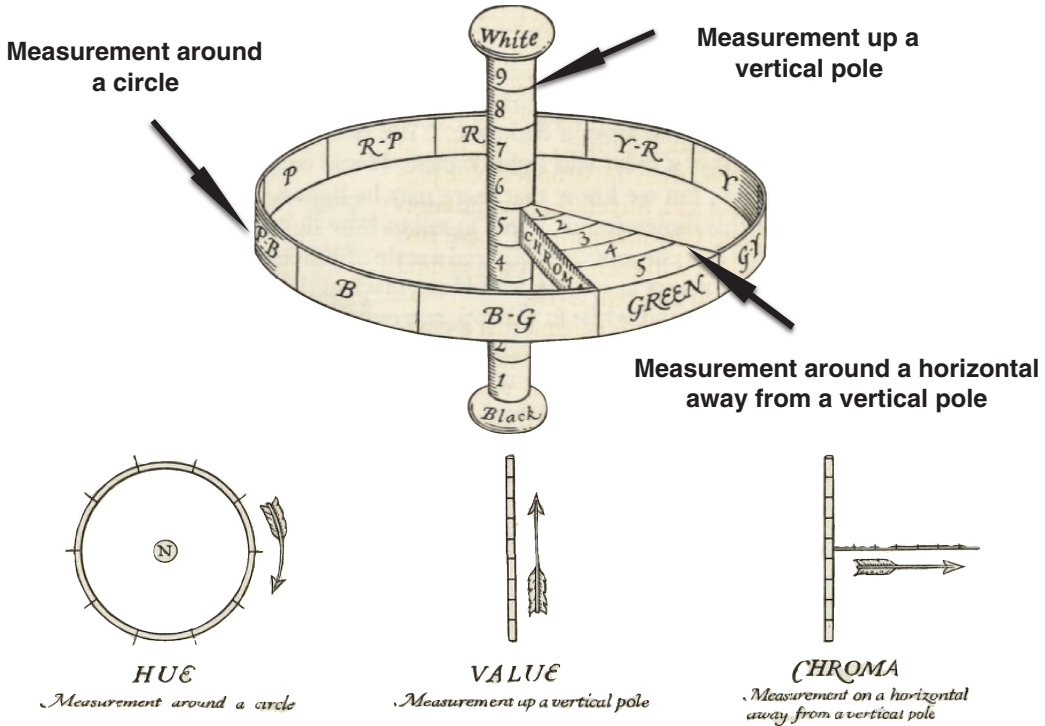


FIGURE 3.11 Combined illustration of the hue, value, and chroma attributes of the three-dimensional Munsell color order system. From Reference [27], public domain. Illustration combines elements from pages 13 and 16 in the above-cited book. Text annotations were added by Theresa-Marie Rhyne, 2015.

3.8.2 Geometry of the Munsell Color Order System

As Figure 3.11 shows, Munsell developed his system as an orb. Around the equator runs a band of colors that defines the “hue” attribute. The axis of the orb encompasses a scale of neutral Gray values with White at the top of the pole and Black at the bottom of the pole. This axis defines the “value” attribute. Extending horizontally from the axis at each Gray value is a gradation of color moving from neutral Gray at the center of the orb to full saturation at the outer ring. This horizontal progression defines “chroma”. Munsell established numerical scales with visually uniform steps for each of the three attributes. We discuss these attributes in further detail below.

3.8.2.1 Hue

The Munsell color order system defines hue attributes as actual colors and establishes five principal hues. These principal hues are Red (R), Yellow (Y), Green (G), Blue (B), and Purple (P) and are equally spaced in a clockwise order around a color circle or wheel.

These principal hues are separated by five intermediate or mixture colors. The intermediate hues are defined as Yellow-Red (YR), Green-Yellow (GY), Blue-Green (BG), Purple-Blue (PB), and Red-Purple (RP). The color wheel is measured off in 100 compass points resulting in 100 steps on the hue circle. Each of the primary and intermediate colors is allocated a range of 10° on the color circle and is located at the midpoint of this segment. In the Munsell notation, primary Yellow is identified as 5Y and is at the midpoint of its segment. 2.5Y indicates Yellow progressing toward Yellow-Red with 7.5Y transitioning toward Green-Yellow. 10Y is the end point of the Yellow segment, positioned equally between the primary Yellow (5Y) and the intermediate Green-Yellow (5GY). This notation concept results in forty standard hue circle divisions. In the Munsell notation, Orange is defined as Yellow-Red. Figure 3.12 shows the Munsell hue circle or color wheel as we described above.

Two colors on opposite sides of the hue wheel are called complementary colors. For 5Y (Yellow), the complementary color in the Munsell notation would be 5PB (Purple-Blue). Combining 5Y with 5PB results in the 5N neutral Gray color at the center of the Munsell hue wheel shown in Figure 3.12. The Munsell color notation system is designed so that each color has a logical relationship to all other colors. This is called color harmony. In Chapter 4, we will discuss color harmony concepts in further detail.

40 Standard Munsell hue circle divisions

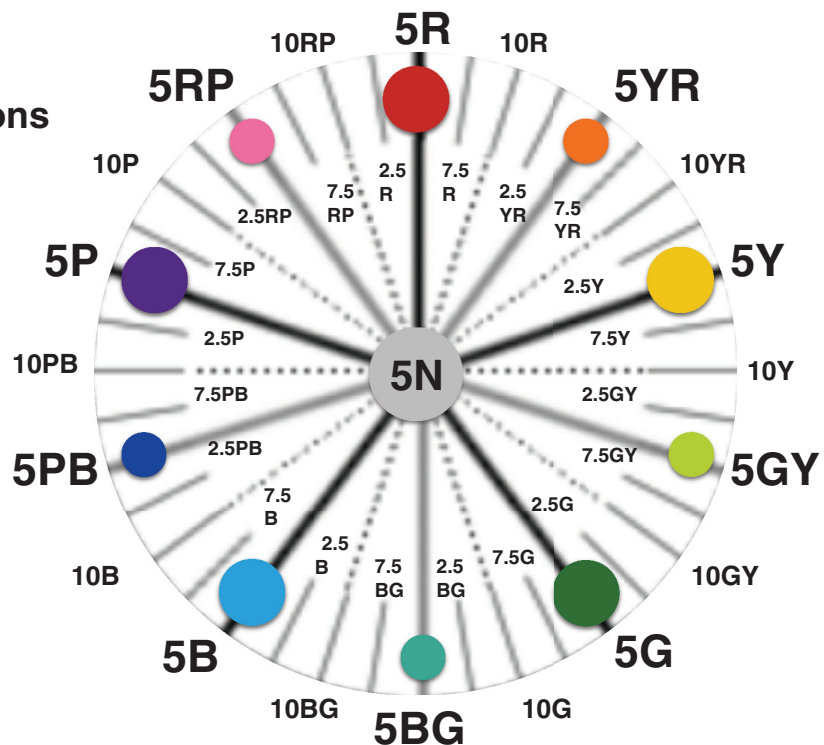


FIGURE 3.12 Munsell hue wheel divided into 40 circle divisions. Illustration by Theresa-Marie Rhyne, 2015, adapted from the, American Society for Testing Materials, ASTM D1535: Specifying Color by the Munsell System, 1968, <https://archive.org/details/gov.law.astm.d1535.1968/page/n9/mode/2up>.

3.8.2.2 *Value*

The value of a color refers to how light or dark a given hue is. In the Munsell color order system, the scale of a value ranges from 0 for pure Black to 10 for pure White along a vertical axis as shown previously in Figure 3.11. Each step is divided into decimal increments and results in a 100-step lightness scale. Black, White, and the Grays between them are defined as having no hue and are called “neutral colors”. The notation N is used to indicate the Gray value at any point on the vertical axis. Colors that have a hue, as noted in our description of the hue attribute above, are called “chromatic colors”. The value scale is applied to chromatic and neutral colors. The value attribute of the Munsell color order system is considered the backbone or “trunk” of the color tree as shown in Figure 3.11. The hue circle or color wheel resides at 5N or at the middle level of the value attribute as noted in Figure 3.12. The value of a specific hue is noted with the value at the end of the hue designation. As an example, 5Y 4/ indicates a Middle Yellow at the value level of 4. The value scale is defined as perceptual or visual. It is based on how humans’ see differences in a relative light and is not based on a set of mathematical values from a light source. Munsell originally developed the original value scale based on human subjects’ perceptual judgments of mixtures of White and Black paints. In Munsell’s original publications, the value attribute ranged from 1 for pure Black to 9 for pure White as Figure 3.11 indicates. The scale range was later changed to be 0 for pure Black and 10 for pure White as we indicated at the start of this discussion on value.

3.8.2.3 *Chroma*

Chroma measures the weakness or the strength of a color. It represents the purity of a color in regard to saturation. A low chroma value contains more Gray or pastel tones. A high chroma value is highly saturated or more vivid in tone. As Figure 3.11 indicates, the chrome axis extends from the value axis at a right angle. Chroma is not uniform across the color space; otherwise, we would have the color sphere that Munsell initially proposed and we previously noted in Figure 3.10. Different hues of the Munsell color space can achieve full or saturated chroma at varying locations in the color space [31,32].

In Figure 3.13, as an example, we examine the 5R (Red) hue and compare its chroma scale with its complement, the 5BG (Blue-Green) at the middle value (5N). In the Munsell notation, the Red hue is noted as 5R 5/ and the Blue-Green hue is noted as 5BG 5/. The chroma scale starts at zero for neutral colors and does not have an end. Figure 3.13 indicates that 5R 5/ (Red) has a chroma scale of 18, while 5BG 5/ (Blue-Green) has a chroma scale of 6. In the Munsell color notation, this fully saturated Red is noted as 5R 5/18, while the fully saturated Blue-Green is noted as 5BG 5/6. So, Red is considered three times as strong as Blue-Green in the middle value (5N) location. Chroma paths can change at different steps on the value scale. In the Munsell color space, Reds, Blues, and Purples attain full saturation at mid-levels (5/-) of the value scale and are stronger hues with higher chroma values at full saturation. Yellows and Greens reach full saturation at high value levels of 7/- or 8/- and are weaker hues with full chroma saturation near the neutral axis. In Figure 3.14, we show fully saturated Red (5R 5/18) and fully saturated Yellow (5Y 9/12), each located at

Differences in chroma scales for two hues of equal value in the Munsell color system

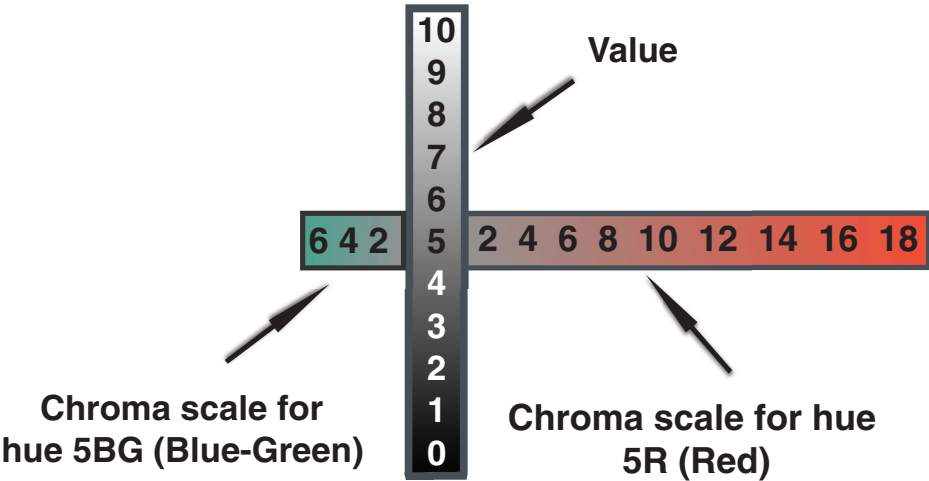


FIGURE 3.13 Differences in chroma scales for two hues of equal value in the Munsell color system. We compare the 5R (Red) hue with its 5BG (Blue-Green) complement at the 5N middle value of the Munsell color system. Source: illustration by Theresa-Marie Rhyne, 2015.

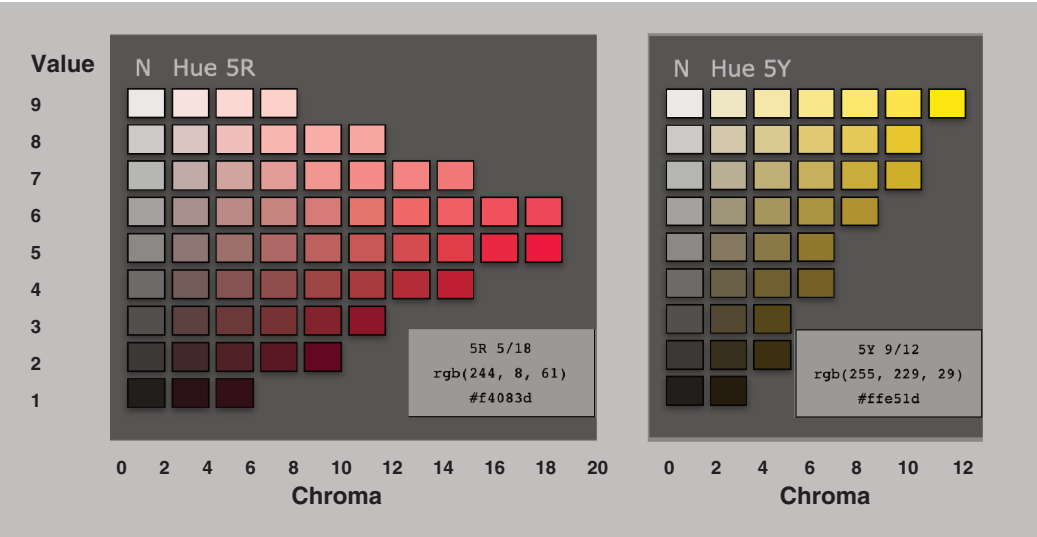


FIGURE 3.14 Comparison of fully saturated Red (5R 5/18) and fully saturated Yellow (5Y 9/12) in the Munsell color space. Image created with the aid of the freely available Virtual Munsell Color Wheel from Andrew Werth, <https://www.andrewwerth.com/aboutmunsell/>. Illustration created by Theresa-Marie Rhyne, 2024.

different value steps, to illustrate this concept (for more details about particular aspects of the Munsell color order system, see References [33–37]).

As highlighted earlier, these differences in chroma values prevent the three-dimensional shape of the Munsell color space from being a symmetrical sphere and Munsell defined the highly asymmetrical shape as a color tree, as shown previously in Figure 3.10. The two-dimensional plots of value and chroma for a given hue depict two branches on the color tree.

3.8.3 Munsell Color Scales and Digital Media

The Munsell color order system dates back to the late 19th century, before the development of digital media. Even today, Munsell colors are standardized as carefully prepared paint chips or color samples that are presented as separate pages in a reference catalog entitled the Munsell Book of Color. Individual pages of the color atlas include color samples of a single hue arranged according to a two-dimensional grid of the value on the vertical axis and chroma on the horizontal axis. These are sometimes referred to as color scales. Colors are determined by placing the color specimen against the atlas samples until a color match is found. Such visual evaluations are considered accurate only if the comparison specimens are as large as the atlas color samples and if a Gray background under the same day light or incandescent illumination is consistently used for assessments. As indicated earlier, the Munsell Book of Color continues to be available from the Munsell Color Company whose website is located at www.munsell.com.

Digital color solutions and libraries have also been developed from the Munsell Book of Color and other standards based on the Munsell color space. ASTM International, an international standards organization that develops and publishes voluntary consensus technical standards, has made available conversion formulas and lookup tables to produce a Munsell equivalent for the CIE XYZ specification. These conversion formulas also facilitate the translation of the Munsell color space to and from any other modern or color systems able to convert to CIE standards. We covered the CIE XYZ color space in Section 3.5 of this chapter. The Munsell Color Science Laboratory provides the digital Munsell hue, value, and chroma and CIE x , y , and Y data for free use. The Munsell Color Science Laboratory is located at the Rochester Institute of Technology with a website at <https://www.rit.edu/science/munsell-color-lab> (see Reference [38]). There are many software applications that are available for creating digital versions of the atlas pages in the Munsell Book of Color. WallkillColor, with their website at <http://wallkillcolor.com>, is one example (see Reference [39]).

Several online and mobile applications are available that provide a digital version of the Munsell Book of Color, converted to sRGB color space for display. We discussed the sRGB color space in Section 3.3 of this chapter. Some of the mobile apps can be found on the Google Play and iTunes online stores. To develop the images previously shown in Figure 3.14, we used the free Virtual Munsell Color Wheel from Andrew Werth's website at <https://www.andrewwerth.com/aboutmunsell/>. The app provides corresponding RGB and Web color hex codes for the Munsell hues shown. It is important to remember that these codes result from the color space conversions we described above and are approximate (see Reference [40]).

Although physical comparison of color specimens to carefully prepared paint chips or color samples can be considered out of date with regard to digital media, it turns out to be one of the more accurate methods of color matching. This is because any digital color library cannot depict color specimens consistently or accurately due to the color gamut constraints of RGB display devices. We defined and highlighted color gamut in Section 3.1 of this chapter.

3.9 HUE, SATURATION, AND VALUE (HSV) AND HUE, SATURATION, AND LIGHTNESS (HSL) COLOR SPACES

The *hue, saturation, and value* and *hue, saturation, and lightness* color spaces are three-dimensional cylindrical coordinate representations of the Red, Green, and Blue (RGB) color model. These models were established to create intuitively easier and more perceptually relevant mixing of additive RGB color lights. Members of the computer graphics community developed HSV, frequently referred to as HSB where B stands for brightness; and HSL, often referred to as HLS, in the 1970s to support computer graphics applications. Today, HSV and HSL color spaces are frequently used in digital color selection and image editing software. We highlight the history, geometric aspects, and the application of HSV and HSL below.

3.9.1 The Challenge of Mixing RGB Lights

As discussed in Section 3.1 of this chapter, combining Red, Green, and Blue (RGB) lights produces the color gamut or color range of display devices. The process of mixing RGB lights to produce various colors is not always intuitive or perceptually relevant. In Figure 3.15, we show how a colorful Yellow of Red = 255, Green = 224, and Blue = 97 can be reduced to what perceptually appears to be half of its colorfulness with a less saturated Yellow of R = 214, Green = 193, and Blue = 118. This results in a decrease in Red by 41, a decrease in Green by 31, and an increase in Blue by 21 as shown in the illustration. This RGB reduction methodology is not necessarily intuitive or logical in our efforts to select digital color combinations.

HSV and HSL color spaces were developed to accommodate more traditional and intuitive ways of mixing colors such as those used by painters for centuries with the Red, Yellow, and Blue (RYB) painters color space. Painters mix bright and colorful pigments with White to achieve a *tint*, with Gray to achieve a *tone* or with Black to achieve a *shade*. In Figure 3.15, these options were not easily available to us when working with the RGB sliders. HSV and HSL color spaces were also designed to address human vision factors like those we covered in Chapter 2 and follow color organization principles of hue, value, lightness, and chroma similar to the Munsell color space implementation covered previously in Section 3.8 of this chapter.

3.9.2 Historical Development of HSV and HSL Color Spaces

In the early 1970s, Richard Shoup and Alvy Ray Smith, at Xerox's Palo Alto Research Center (PARC), pioneered the development of computer painting programs (see [41]). Smith conceptualized the HSV color space during this time frame. Smith then moved on

Reducing colorfulness in RGB color space is not always logical.

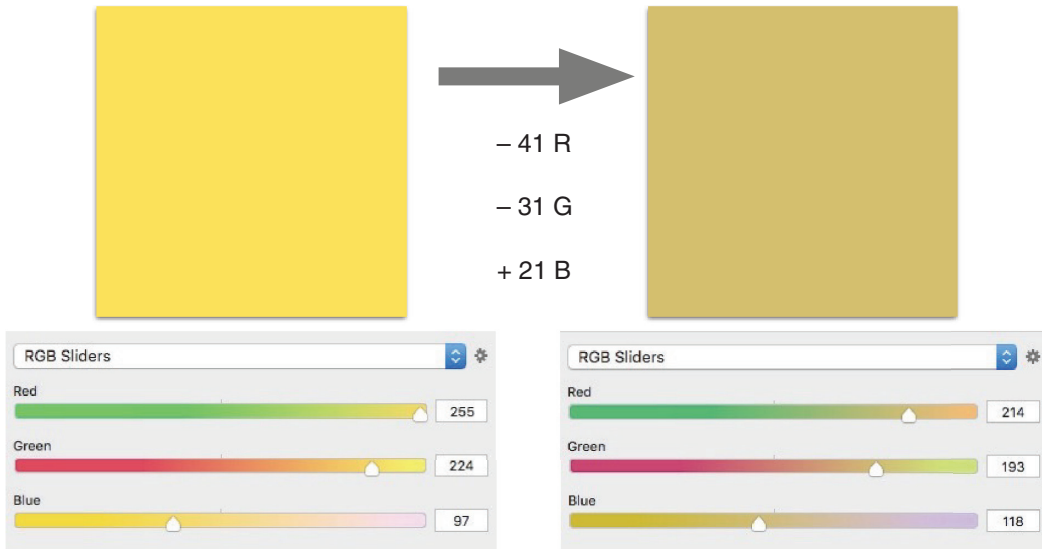


FIGURE 3.15 Illustration of how color specification and modification are not always intuitive when working directly with the RGB values. Source: illustration by Theresa-Marie Rhyne, 2015.

to the Computer Graphics Laboratory at the New York Institute of Technology (NYIT) that would later evolve into the Pixar Animation Studios in Emeryville, California. In August 1978, Smith presented his paper on HSV at the annual Association for Computing Machinery's Special Interest Group on Graphics Conference (SIGGRAPH 1978). The paper "Color Gamut Transform Pairs" defined HSV and was published in the conference proceedings. George H. Joblove and Donald Greenberg of Cornell University also presented the HSL color space and compared it to HSV at SIGGRAPH 1978. The Joblove and Greenberg paper was entitled "Color Spaces for Computer Graphics" [42,43].

The conversions from RGB values to HSV or HSL color spaces could be rapidly computed and easily ran in real time on computer graphics hardware of the late 1970s and early 1980s. By SIGGRAPH 1979, the Computer Graphics Standards Committee recommended and supported these color spaces. Also, at SIGGRAPH 1979, Tektronix Inc. introduced computer graphics terminals that relied on HSL for its color designations. The HSV and HSL color spaces, as well as similar ones, were also built into computer graphics software and image editing tools over the years. The ubiquitous nature of these color spaces can be seen in their coverage in fundamental computer graphics textbooks, even today. For example, the editions of the *Computer Graphics: Principles and Practice* review the mathematics behind HSV and HSL [44]. We refer you to this textbook and the original HSV and HSL research papers noted above for further details on the mathematics behind HSV and HSL. Today, HSV and HSL continue to be used widely in applications for color selection in computer graphics design and image analysis.

3.9.3 The Geometry of HSV and HSL

HSV and HSL both use three axes to define their respective color spaces. The HSV color space is usually represented as a cone or hexcone. The cone defines the subset of the HSV space with valid RGB values. Similarly, the color solid for the HSL color space is a double cone or double hexcone. The three-axis approach is in some ways analogous to the Munsell color order system, covered in Section 3.8. HSV defines hue, saturation, and value where value is sometimes referred to as brightness. HSL defines hue, saturation, and lightness where sometimes the order is noted as HLS. We describe these parameters below.

3.9.3.1 Defining Hue

In HSV and HSL, hue is used to describe the degrees of color. The specification of the hue axis ranges from 0 to 360. This forms a color or hue wheel that begins and ends in Red (0/360) and encompasses Yellow (60), Green (120), Cyan (180), Blue (240), and Magenta (300). Examining these specifications more carefully indicates that these hue ranges specifically address the primary colors of the RGB color model for lights and the Cyan, Magenta, and Yellow primary colors of the CMYK color model for printing we noted in Chapter 1. The Red (0/360), Green (120), and Blue (240) (RGB) hues form a triangle when connected by straight lines on the hue wheel. The same is true for Cyan (180), Magenta (300), and Yellow (60) (CMY) hues. We will highlight further details about the location of hues on various color wheels in Chapter 4 of this book. Figure 3.16 diagrams specific colors on the hue axis for the HSV and HSL color spaces.

Diagram of the HSV and HSL color wheel

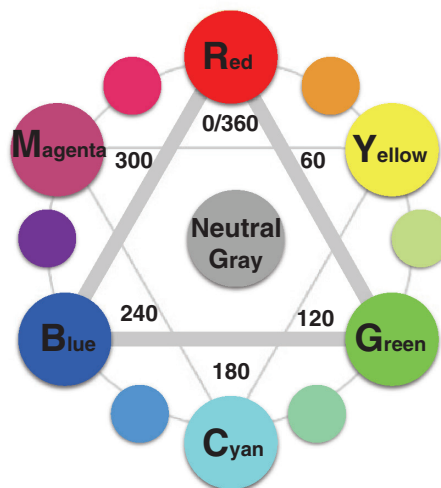


FIGURE 3.16 Diagram of the hue or color wheel that depicts the colors associated with the hue axis in the hue, saturation, and value (HSV) and hue, saturation, and lightness (HSL) color spaces. Source: illustration by Theresa-Marie Rhyne, 2015.

3.9.3.2 Defining Saturation

Saturation indicates the degree that a hue differs from neutral Gray in the color space. It ranges from 0% for no color or desaturation to 100% for a pure color or full saturation. In Figure 3.16, the colors on the outer edge of the hue wheel are pure colors. As we move into the center of the wheel, more Gray is added to the various hues, resulting in the colors dominating less and less. A faded hue or tone indicates the color contains more Gray. At the center of the wheel, the neutral Gray zone is reached, and no hue dominates. The center of the wheel is the zone of complete desaturation, while the outer edge of the hue wheel is the region of full saturation. Saturation has similarities to the chroma parameter of the Munsell color order system that we highlighted in Section 3.8 of this chapter. In Figure 3.17, we illustrate the degrees of saturation for the Yellow hue ranging from 0% for no color or neutral Gray to 100% for a pure Yellow hue.

3.9.3.3 Defining Value

Value is the brightness of the hue and varies with color saturation in the HSV color model. Value ranges from 0% where the color space is completely Black to 100% where the colors

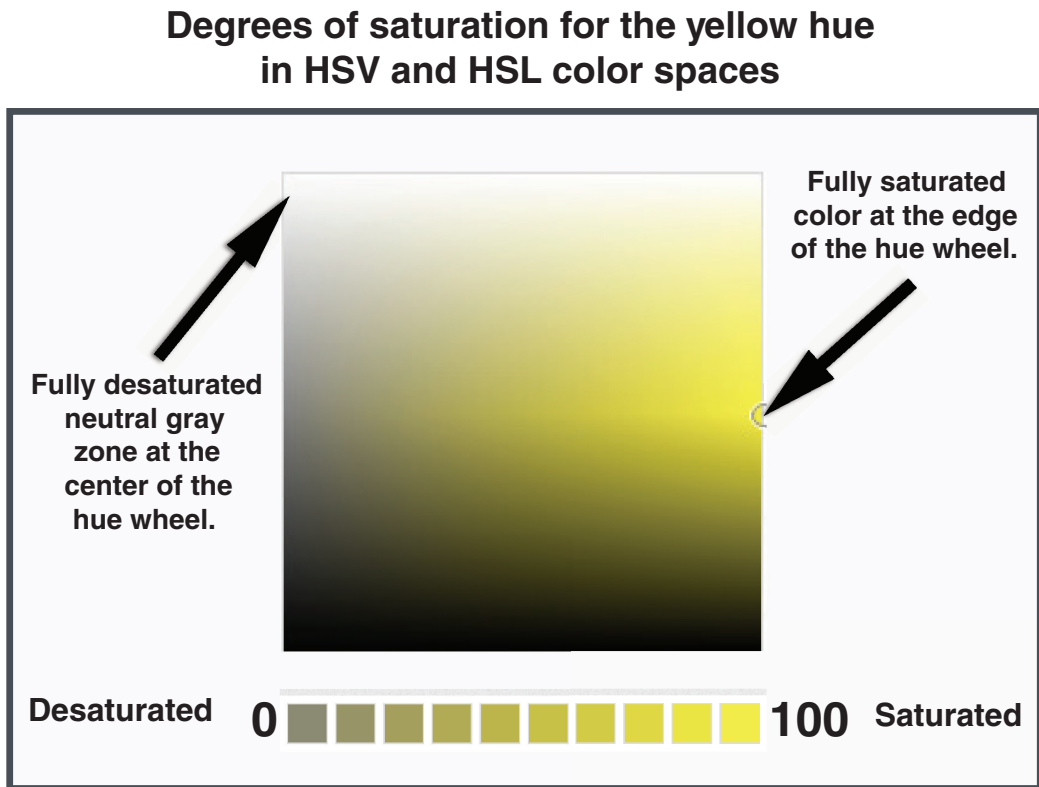


FIGURE 3.17 Degrees of saturation for the Yellow hue in HSV and HSL color spaces are shown. Source: illustration by Theresa-Marie Rhyne, 2015 & 2024. Yellow color example generated with the use of the Mozilla Development Network's Color picker tool at https://developer.mozilla.org/en-US/docs/Web/CSS/CSS_Colors/Color_picker_tool.

Geometry of hue, saturation, and value (HSV) color space

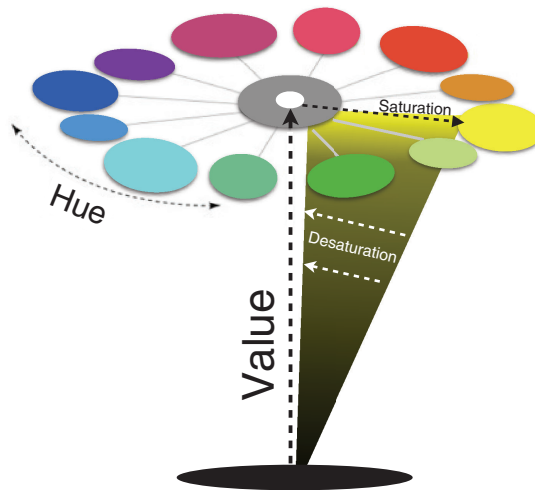


FIGURE 3.18 Geometry of the HSV color space. Source: illustration by Theresa-Marie Rhyne, 2015.

are on the hue wheel. Value is a linear axis running through the center of the hue wheel as shown in Figure 3.18. With Figure 3.18, we also show the full range for the color Yellow in the HSV color space.

3.9.3.4 Defining Lightness

Lightness indicates the level of illumination in the HSL color space. Lightness ranges from 0% for Black (no light) to 100% for full illumination that washes out the hue so it appears as White. Hues at less than 50% appear darker, while hues at greater than 50% appear lighter. As shown in Figure 3.19, the hue color wheel is located at the 50% value of the lightness scale in the HSL color space. Figure 3.19 also depicts the full range for the color Yellow in the HSL color space.

3.9.4 Comparison of HSV and HSL Color Spaces

HSV and HSL differ in the geometric shape of their color spaces as shown in Figure 3.18 and Figure 3.19 respectively. The HSV color space is represented as a single cone, while the HSL color space is depicted as a double cone. For both geometric shapes, the central vertical axis represents an achromatic or a neutral axis with Black at the bottom at a value = 0 in HSV and lightness = 0 in HSL. White is at the top of the central axis with value = 1 in HSV and lightness = 1 in HSL. The hue circle of colors is positioned in both color spaces around the edge of the geometric shape at saturation = 1. In HSV, the hue circle is positioned at the top of the cone with a value = 1. In HSL, the hue circle is positioned in the middle of the double cone with lightness = 0.5. This positioning results in some differences in the mixing of the pure colors on the hue circle outer edge. In HSV, mixing pure colors with White

Geometry of hue, saturation, and lightness (HSL) color space



FIGURE 3.19 Geometry of the HSL color space. Source: illustration by Theresa-Marie Rhyne, 2015.

reduces saturation, yielding tints, while mixing pure colors with Black leaves saturation scales unchanged, resulting in shades. With HSL, both tints and shades have full saturation, while tones, mixtures with both Black and White, have saturation levels less than 1.

A key advantage to HSV is its conceptual simplicity since each attribute corresponds to color concepts we noted in Chapters 1 and 2. As noted previously, the saturation attribute in HSV corresponds to tinting with desaturated colors having increasing total intensity. This is considered a limitation to the HSV color space. As a result, the Cascading Style Sheets (CSS) standard for Web content development supports RGB and HSL but not HSV. We will highlight color standards for the Web in Section 3.11 of this chapter.

HSV and HSL are computationally efficient color spaces for color selection while creating the digital content. A key disadvantage of the HSV and HSL color spaces is in regard to addressing the complexity of the color appearance such as perceptual uniformity. Both color spaces are not absolute color spaces like the CIE color spaces described previously in Section 3.6 or the Munsell color order system reviewed in Section 3.8. In Section 3.10, the HCL color spaces will be covered that are based on cylindrical transformations of CIE LUV or CIE LAB.

HSV and HSL are defined purely with reference to a given RGB space. As we noted in Section 3.3, there are many commonly applied RGB color spaces. As a result, a precise specification of a color involves noting the HSV or HSL attributes, as well as the characteristics of the referenced RGB color space and the associated gamut correction in use. Fundamentally, HSV and HSL color spaces trade off perceptual uniformity for

computational speed. There are many digital content creation situations, such as interactive visualization, real-time virtual environments, or computer game development, where such computational speed is optimal.

3.9.5 Example of Color Selection Application Using HSV and HSL

The HSV and HSL color spaces are designed to support effective color “picking” while creating the digital media content. Therefore, these color spaces are most commonly applied to color selection tools. Many of these color selection tools provide three sliders for each attribute of the respective color space. In Figure 3.20, we show the “Color picker tool”, a free community-built online color selection resource intended for all Web developers and content creators from the Mozilla Development Network (MDN) [45]. In the application, both HSV and HSL color attributes are provided. The Color picker tool is available online at https://developer.mozilla.org/en-US/docs/Web/CSS/CSS_Colors/Color_picker_tool.

In Figure 3.20, we can compare and contrast the HSV and HSL attributes for a Yellow color where the RGB values are R = 237, G = 230, and B = 52. In the HSV color space, H = 57, S = 78, and V = 92. In the HSL color space, H = 57, S = 83, and L = 56. The hue attribute, H = 57, is constant in both color spaces. The saturation attribute varies slightly between color spaces for this Yellow color. In the HSV space, S = 78, while in the HSL space, S = 83. It is anticipated that a color with a value in HSV of 92 would have a lightness attribute of nearly half in the HSL space. With this Yellow color, L = 56 in the HSL space. As to be expected by the geometry of the two color spaces, this Yellow color registers at the top of the HSV color space and in the middle range of the HSL color space. The numerical

Example of a free & online
HSV and HSL color selection tool

(https://developer.mozilla.org/en-US/docs/Web/CSS/CSS_Colors/Color_picker_tool)

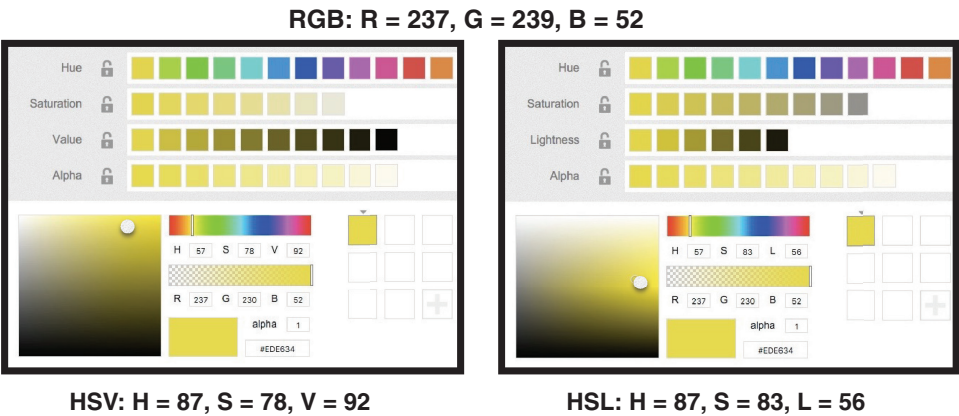


FIGURE 3.20 Example of a free and online HSV and HSL color selection tool entitled “Color picker tool” (https://developer.mozilla.org/en-US/docs/Web/CSS/CSS_Colors/Color_picker_tool). Source: illustration by Theresa-Marie Rhyne, 2015 & 2024, using the Color picker tool with additional annotations for clarification.

specifications of these attributes correspond to the geometric differences in HSV and HSL color spaces as diagrammed in Figures 3.18 and 3.19. In Section 3.11 of this chapter, we will highlight this “Color picker tool” further to illustrate color formats associated with Web development.

3.10 HCL AND LIGHTNESS, CHROMA, AND HUE (LCH) COLOR SPACES

HCL color spaces are tailored to human color perception and attempt to address perceptual uniformity. A color space is perceptually uniform if a change of length in any direction X of the color space is perceived by a human as the same change. A non-uniform perceptual color map can have stark contrasts when transitioning from one hue to another hue. Figure 2.18 in the previous chapter showed the difference between non-perceptual uniform and perceptual uniform rainbow color maps. RGB, HSV, HSL, and CIE XYZ, while having many advantages, are not perceptually uniform. The Munsell, CIE LUV, and CIE LAB represent attempts at creating human perceptual uniform color spaces. HCL, sometimes referred to as lightness, chroma, and hue (LCH), color spaces merge many of the concepts of other color spaces. Similar to how HSV and HSL transform RGB spaces by extending two-dimensional polar coordinates to three dimensions, HCL spaces perform cylindrical transformations of CIE LUV or CIE LAB for optimized perceptual uniformity.

Figure 3.21 shows the RGB and the HCL color wheels and spectrums to visually compare the difference between non-uniform (RGB) and uniform (HCL) perceptual color spaces. When the respective color spectrums are converted to Grayscale diagrams, it is easier to

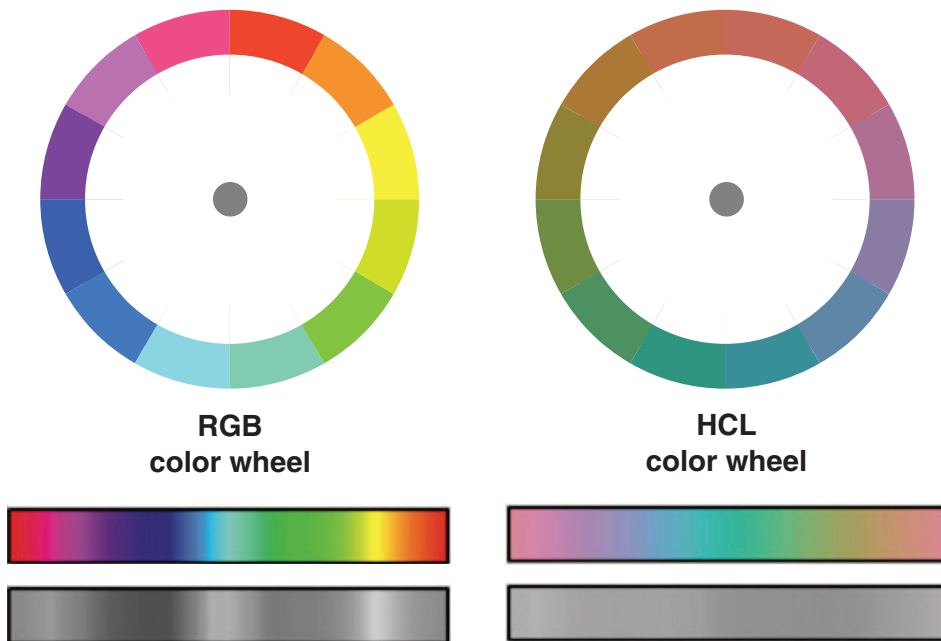


FIGURE 3.21 Comparison of the RGB (non-uniform) and the HCL (uniform) color wheels and spectrums. Illustration by Theresa-Marie Rhyne, 2024. The HCL wheel created with the aid of the Colorpicker for data online app, <http://tristen.ca/hcl-picker/#/hlc/6/1/15534C/E2E062>.

conceptualize the uneven nature of the RGB color space and the nearly consistent nature of the HCL color space. The RGB color wheel and spectrums are based on concepts that were covered in Chapter 2. The HCL color wheel was created with the aid of *Colorpicker for data*, an online HCL app designed by Tristen Forsythe Brown. *Colorpicker for data* is freely available at <http://tristen.ca/hcl-picker/#/hlc/6/1/15534C/E2E062> [46].

3.10.1 The Geometry of HCL

HCL uses three dimensions to describe color:

- Hue (dominant wavelength, referring to color in the visible spectrum);
- Chroma (colorfulness, intensity of color as compared to Gray);
- Luminance (brightness, amount of Gray).

For a specific luminance (L) parameter, all colors resulting from different combinations of hue (H) and chroma (C) will have the same level of brightness. This means that when converted to a Gray scale, the colors will appear nearly identical. This is shown in the HCL color wheel of Figure 3.21. As Munsell [25] noted in the early 1900s, this concept of near-perceptual uniformity produces an oddly shaped and a far from geometrically regular color space. There are also mapping challenges between HCL and RGB color spaces. It is possible to select an HCL color that cannot be displayed in an RGB format. Figure 3.22 shows screenshots from Michael Horvath's three-dimensional implementations of the RGB gamut for the cylindrical coordinate versions of CIE LUV and CIE LAB. These HCL color spaces are frequently referred to as *polarized* CIE LUV or *polarized* CIE LAB. A more detailed discussion on the motivation and mathematics of hue, chroma, and luminance can be found in the technical discussion by Zeileis, Fisher, Hornik, Ihaka, McWhite, Murrell, Stauffer, and Wilke, "Colorspace: A Toolbox for Manipulating and Assessing Colors and Palettes" [47].

There are tools or apps for color scheme creation and selection based on the HCL color space. Several of these will be featured in Chapter 6 of this book.

3.10.2 Perceptual Uniformity and Color Deficiency

As covered in Chapter 2, in humans there are three types of photoreceptors or cones where each is sensitive to different parts of the visual spectrum of light. These three different photoreceptor elements combine to facilitate rich color vision. If one or more of the set of cones does not perform properly, a color deficiency results. A Red cone deficiency is classified as *protanopia*. A Green cone deficiency is classified as *deutanopia*. A Blue cone deficiency is classified as *tritanopia*.

Color combinations or schemes selected in a perceptual uniform color space might not pass color deficiency. Figure 3.23 shows simulations of how the HCL color wheel appears to individuals with protanopia, deutanopia, and tritanopia. The Color Blindness Simulator (Coblis) online app was used to create the results for this illustration [48].

Two versions of hue, chroma, and luminance (HCL)



HCL: Polarized version of CIE LUV

HCL: Polarized version of CIE LAB

FIGURE 3.22 Two versions of the hue, chroma, and luminance (HCL) color space: polarized CIE LUV and polarized CIE LAB. 3D implementations. Images created by Michael Horvath (Shark D) and Christoph Lipka on March 29, 2017, and in the public domain (creative commons) by the request of the creators, https://en.wikipedia.org/wiki/File:SRGB_gamut_within_CIELCHuv_color_space_mesh.webm and https://en.wikipedia.org/wiki/File:SRGB_gamut_within_CIELCHab_color_space_mesh.webm.

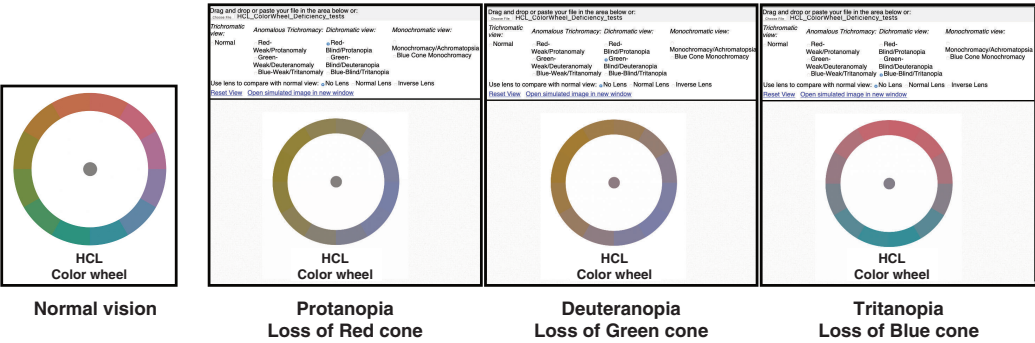


FIGURE 3.23 Color deficiency checks for the hue, chroma, and luminance (HCL) color wheel using the Color Blindness Simulator (Coblis). Source: illustration created by Theresa-Marie Rhyne, 2024.

These HCL color wheel tests depict a very limited range for creating color contrasts that also pass color deficiency. Checking color combinations for color deficiency becomes a key parameter in building accessible digital media and data visualization color schemes. We will highlight and demonstrate these factors with examples and case studies in Chapters 6 and 7 of this book.

3.10.3 Oklab and Oklch

As Section 3.7 briefly noted, in 2020, a perceptually uniform color space that combined the structure of CIE LAB with improved CAM16 data was introduced as Oklab [22]. The three dimensions for Oklab are as follows:

- L – perceived lightness;
- a – level of Green/Red for the given color;
- b – level of Blue/Yellow for the given color.

These axes are based on Ewald Herring’s opponent color theory noted in Chapter 2.4 and diagrammed previously as the CIE LAB color space in Figure 3.9. The differences are in the mathematics and data derived from newer color appearance models. In terms of lightness, chroma, and hue (LCH) criteria, Oklab has improved performance when compared against other color spaces, such as CIE LUV, CIE LAB, HSV, and CAM16 UCS [49]. Bjorn Ottoson developed Oklab and describes his motivation and derivations in Reference [22]. When Oklab is converted into cylindrical coordinates or *polarized*, it is called Oklch. The impressive results of Oklab and Oklch as perceptual uniform color spaces have resulted in their 2023 acceptance and incorporation into most Web browsers. Section 3.11 of this book will discuss Web colors and standards.

3.11 WEB COLORS AND HEX TRIPLETS

In developing content for the Web, there are standards for describing and specifying colors for text and graphics. These guidelines are currently monitored and maintained by the World Wide Web Consortium (W3C) [50]. The CSS Color Module Level 4 specification allows a *Web color* to be specified in a variety of ways according to many of the color spaces we have discussed in this chapter. These include RGB, HSL, CIE LAB, LCH, Oklab, and Oklch. In setting parameters for displaying Web pages, colors can be defined according to the format of these color spaces or in a hexadecimal (hex triplet) format [51]. In some cases, Web colors can also be noted according to their English name. The hex triplet format, with a leading number sign (#), is the most common format used. Figure 3.24 presents Web colors on an RGB color wheel with a table for noting the English name, RGB value, and hex triplet value for each hue.

3.11.1 Defining Hex Triplets or Color Hex Codes

A hex triplet is a six-digit and three-byte hexadecimal number used to represent a color in the Hypertext Markup Language (HTML), Cascading Style Sheets (CSS), Scalable Vector Graphics (SVG), Extensible 3D Graphics (X3D), and other Web applications. The bytes refer to the Red, Green, and Blue components of the color where byte 1 refers to the Red value, byte 2 refers to the Green value, and byte 3 refers to the Blue value. The hexadecimal notation uses 16 distinct symbols where 0–9 represent values zero to nine and A, B, C, D, E, and F represent values 10–15. For a Web color, 1 byte represents a number in the range

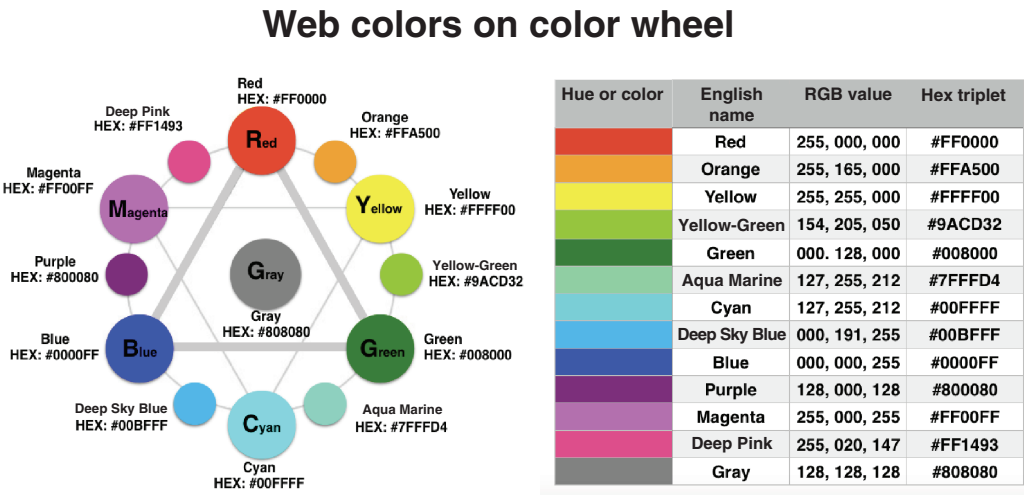


FIGURE 3.24 Web colors on a color wheel. In this illustration, we show appropriate Web colors on an RGB color wheel and provide a table for noting the English name, RGB value, and hex triplet value for each hue. Source: illustration by Theresa-Marie Rhyne, 2016 & 2024.

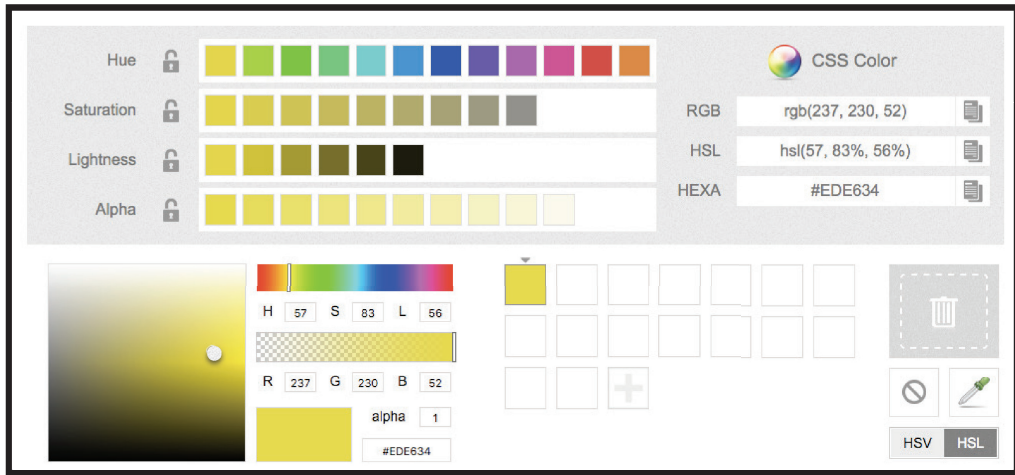
of 00–FF. Using our previous example in Figure 3.20, for the Yellowish color where R = 237, G = 230, and B = 52 in the RGB color space, the hexadecimal numbers are ED, E6, and 34. The hex triplet value is noted as #EDE634 where the hexadecimal numbers are concatenated together. If any of the 3 bytes have a color value that is less than 16 (in hexadecimal notation) or 10 (in decimal notation), it must be represented with a leading zero so that the triplet always has six digits.

For example, pure Yellow where R = 255, G = 255, and B = 0 has a hex triplet value of #FFFF00. It takes 24 bytes to specify a given color in this notation system, and the total number of colors that can be specified is 256 to the exponential power of 3 or 16,777,216. Today, the majority of color selection tools automatically convert between RGB and hex triplet values. This is true of the “Color picker tool” we discussed previously in Section 3.9.5 of this chapter. In Figure 3.25, we show the full user interface of the Color picker tool where the RGB, HSL, and hex triplet values are noted together for our Yellowish color of R = 237, G = 230, and B = 52 or #EDE634. Hex triplets are sometimes referred to as *color hex codes* and are *not case-sensitive*, so #EDE634 and #ede634 are the same Yellowish color.

3.11.2 HTML, CSS, and SVG Web Colors

The Hypertext Markup Language (HTML), Cascading Style Sheets (CSS), and Scalable Vector Graphics (SVG) are key technologies for creating Web pages [52]. The HTML provides the foundation or the structure for the Web page. The CSS defines the page’s presentation, including colors, fonts, and layout. The SVG is the W3C open standard for supporting two-dimensional graphics in Web pages including interactivity and animation. The CSS Color Module recommendation is the guiding document in regard to applying color to Web pages and is available online at <https://www.w3.org/TR/css-color-4/>.

Example color selection tool with Web colors specified in RGB, HSL, & HEX values



RGB: R = 237, G = 230, B = 52 HSL: H = 57, S = 83, L = 56 HEX: #EDE634

FIGURE 3.25 Example of color selection tool with Web colors specified in RGB, HSL, and hex triplet values using the Color picker tool (https://developer.mozilla.org/en-US/docs/Web/CSS/CSS_Colors/Color_picker_tool). Source: illustration by Theresa-Marie Rhyne, 2015 & 2024, using the Color picker tool with additional annotations for clarification.

At the time of the writing of the 2nd edition of this book, the CSS Color Module Level 4 recommendation, as of February 13, 2024, is moving toward acceptance. As noted earlier, the CSS Color Module also outlines how to specify Web colors according to several color spaces mentioned previously in this chapter. These color spaces are noted here with the corresponding sections in Chapter 3 where they were introduced. They include HSL (Section 3.9), CIE LAB (Section 3.6.2), LCH (Section 3.10), Oklab (Section 3.10.3), and Oklch (Section 3.10.3). Most color selection tools and apps include RGB and hex triplet formats at a minimum.

3.11.3 Web Safe Colors

Web safe colors consist of 216 colors that display solid and non-dithered colors consistently on any display device supporting at least an 8-bit color (256 colors). Today's display technologies typically support a 24-bit color or better, so the need for Web safe color consideration is becoming obsolete. However, we review the Web safe concepts here.

Historically, many computer monitors were only capable of displaying in an 8-bit color that included only 256 colors. If an image or graphic contained a color not within the 256 colors of the display monitor, a substitute color was applied, or dithering was used to try to approximate the color. Using the substitute color option often resulted in the

closest color being applied with unexpected results frequently occurring. The dithering solution slowed down the loading of the graphic or image due to the calculations involved in creating the color. To avoid this situation, a set of “Web safe colors” became necessary. The number 216 was selected since computer operating systems typically reserved 16–20 colors for their own use. The number 216 also allowed for six equally spaced shades for Red, Green, and Blue (RGB values from 0 to 255) and also supported the 00-to-FF range in the hexadecimal notation (hex triplets). This mathematical relationship can be simply noted as $6 \times 6 \times 6 = 216$.

The Web safe colors developed were based on mathematics and not aesthetics or color theory. The 216 colors contain RGB values of 0, 51, 102, 153, 204, and 255 where RGB values range from 0 to 255. These numbers are multiples of 51 or 20% of 255 and result in the six equally spaced shades of RGB values at 0%, 20%, 40%, 60%, 80%, and 100% as we noted above. In hex triplet equivalents, the 216 colors contain hex values of 00, 33, 66, 99, CC, and FF. Many lookup tables have been developed that present the entire range of the 216 Web safe colors. Two excellent resources are at <https://htmlcolorcodes.com/color-chart/web-safe-color-chart/> and <http://cloford.com/resources/colours/websafe1.htm> [53,54].

As noted earlier in this section, Web safe colors have become an obsolete concept since modern display devices now support at 24-bit color levels or better. As we have shown, the concept is based on mathematics and not aesthetics or color theory. However, it is helpful to be aware of the Web safe terminology and the rationale behind its usage.

3.11.4 An Example of Using Color Hex Codes with a Text-Based Generative AI Tool

Text-based generative artificially intelligent (generative AI) systems allow users to ask a chatbot for assistance in tasks such as creating emails, essays, and code. There are numerous reviews about the functionality of these tools [55]. For this example, Chat Generative Pre-trained Transformer (ChatGPT) [56] will be used. OpenAI introduced their chatbot to the public on November 30, 2022. The basic version of ChatGPT 3.5 is free to use. It is this version we are featuring here. In general, a text-based generative AI tool cannot create or display images directly. However, the chatbot can respond positively to creating a color scheme with color hex codes (hex triplets).

If ChatGPT is asked to “Use color hex codes to create a blue sequential color scheme”, the chatbot responds with a color hex code sequence. The precise response is shown below.

A blue sequential color scheme typically consists of various shades of blue arranged in a sequential order, creating a smooth transition from one shade to the next. Here’s a simple example of a blue sequential color scheme using hex codes:

1. *Lightest Blue*: #B3E0F2;
2. *Light Blue*: #66B2FF;
3. *Medium Blue*: #337AB7;
4. *Dark Blue*: #1F3A93;
5. *Darkest Blue*: #0E1D6D.

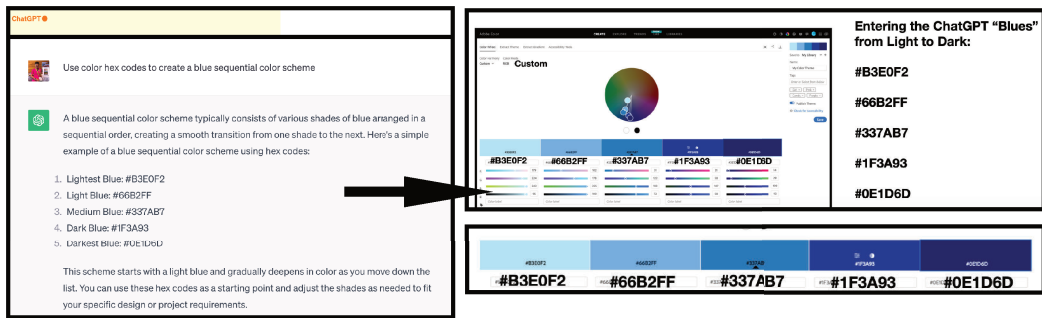


FIGURE 3.26 Example of a text-based generative AI (ChatGPT) tool specifying a Blue sequential color scheme with color hex codes. The five-step color scheme is visually mapped using the Adobe Color online app. Source: illustration by Theresa-Marie Rhyne, 2024, using ChatGPT and Adobe Color with additional annotations added for clarification.

This scheme starts with a light blue and gradually deepens in color as you move down the list. You can use these hex codes as a starting point and adjust the shades as needed to fit your specific design or project requirements.

The next step is to use a tool, like Adobe Color [57], to visually map out the color hex codes ChatGPT specified. These results are in Figure 3.26.

Chapters 4 and 5 will discuss in further detail the color harmony and the building on data color schemes.

3.11.5 An Example of Color Capture and Web Color Selection with a Mobile App

There are many mobile and online apps that allow for selecting colors from an existing graphics file or digital photograph. The colors selected usually appear as color swatches with the Web color noted in RGB and hex triplet formats. Here, we show how to select colors with the Color Companion mobile app, from Digital Media Interactive LLC, for the iPhone or iPad. This app is available for purchase from the iTunes Store, and more details are noted at <https://itunes.apple.com/us/app/color-companion-analyzer-converter/id477794973?mt=8> [58].

For this example, we import a digital photograph from our iPhone directly into the Color Companion app. The image is of a spring garden. Color Companion analyzes the image and determines colors for us to select as a possible color palette. We select a palette of four colors from the digital image. This selection process is shown in the middle image of Figure 3.27. After naming and saving the color palette, we can scroll down to see the four Web colors of our color scheme as hex triplets. For our example, we saved the color palette as “Spring Garden”.

The right image of Figure 3.27 shows the hex triplets of the Spring Garden color scheme. Color Companion also provides the RGB, Lab, HSB (hue, saturation, and brightness), and CMYK values of the four colors selected. We discussed the various color systems associated with these values in previous sections of this chapter (please see Section 3.6.2 for a

Using a mobile app to select web colors

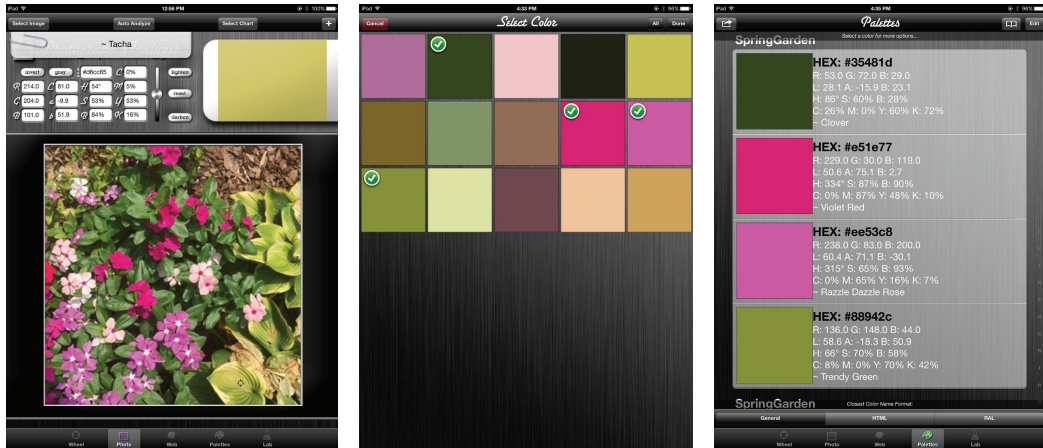


FIGURE 3.27 Using a mobile app to select Web colors. Source: illustration by Theresa-Marie Rhyne, 2016 & 2024, using a personal digital photograph with the Color Companion app from Digital Media Interactive LLC.

discussion on CIE Lab values). In Section 3.9, we provide a discussion on the HSV color model that is frequently referred to as the HSB model. In Chapter 4, we discuss further how to build color schemes and the principles of color harmony.

3.12 PANTONE COLOR MATCHING SYSTEM

The Pantone color matching system (PMS) is a proprietary color space used primarily in printing and in a wide range of other industries including cosmetics, colored paint, fabric, and plastics. Pantone matching methods have evolved into a standardized color reproduction system that utilizes the Pantone numbering system to identify colors [59]. Individuals located in different geographic locations can refer to particular PMS values to insure that colors match without making direct personal contact with each other. The Pantone color guides consist of narrow cardboard sheets (approximately 6 by 2 inches or 15 by 5 cm) that are printed on one side with rectangular samples showing the different Pantone colors. The guide is bound together at the one end to allow for opening the strips out in a fanlike manner. Pantone also provides binders with rectangular swatches and digital media solutions [60]. In 2009, Pantone released the myPantone app for iOS and Android devices. In August 2016, the Pantone Studio app became available. It was replaced by Pantone Connect in the summer of 2020. Pantone Connect is the current version available as a website (<https://www.pantone.com/pantone-connect>) and mobile app. The mobile app can be obtained online from the Apple App Store, Google Play, and Adobe Exchange. We will highlight the website and mobile Pantone Connect app later in Section 3.12.3. See Figure 3.28 for an illustration of a virtual Pantone fan deck from the original myPantone app and how it has transitioned to digital color swatches with the Pantone Connect app.

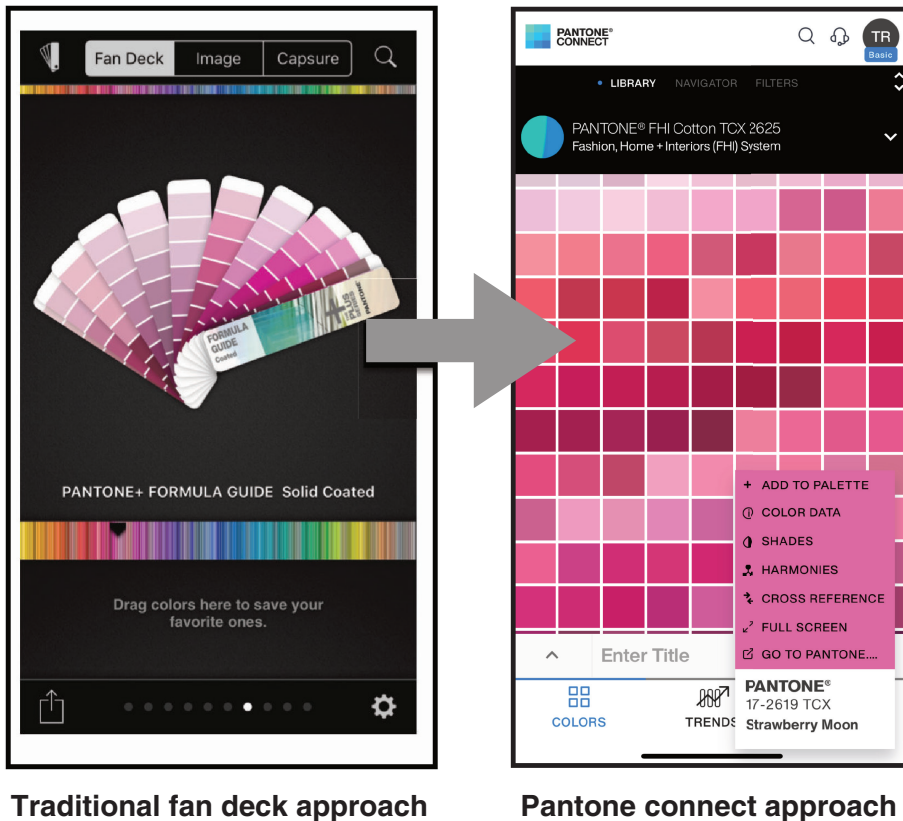


FIGURE 3.28 Progression from the virtual fan deck of the older myPantone app to the new digital swatches of the Pantone Connect app. Source: illustration by Theresa-Marie Rhyne, 2024, using the older myPantone and new Pantone Connect apps from Pantone.

3.12.1 Evolution of the Pantone Management System

The origins of Pantone go back the 1950s when Lawrence Herbert joined M&J Levine Advertising's small commercial printing company [61,62]. Herbert used his chemistry background to simplify the company's production of inks to a set of 12 stock pigments from a full range of colors. By 1962, Herbert was leading the printing division that was profitable, while other aspects of M&J Levine Advertising were not. Herbert purchased the printing division and renamed it to Pantone in 1962. The first Pantone Matching System Printer's Edition was introduced in 1963. By the end of the 1970s, PMS had become a standard in wide international usage. In 1984, Pantone formed its Electronic Color Systems Division to reproduce its color management system into a digital format. In the 1990s, Pantone partnered with leading hardware and software companies to pioneer color management of digital media and printing. By the 2000s, Pantone was a recognized leader in color management and began providing translations of their PMS values to sRGB and Lab formats. In 2007, X-Rite, Inc., a supplier of color measurement equipment, purchased Pantone Inc. In 2012, Danaher Corporation acquired X-Rite, Inc. Interestingly, both Pantone LLC (<https://www.pantone.com>) and the Munsell Color

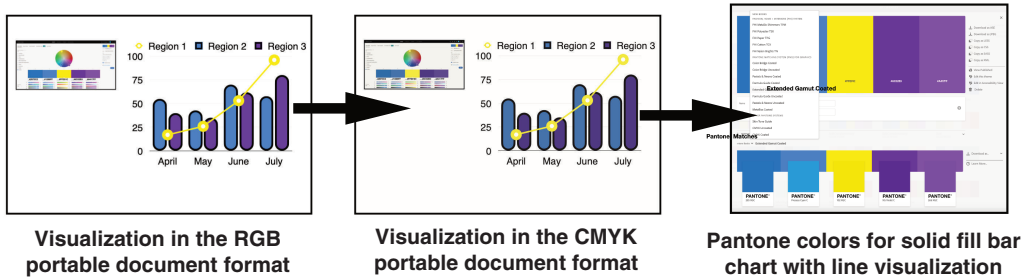


FIGURE 3.29 Selecting Pantone colors to enhance the CMYK color printing process. The Adobe Color app is used for the specification efforts. Source: illustration by Theresa-Marie Rhyne, 2024, using the Adobe Color app.

Company (<https://munsell.com>), highlighted previously in this chapter, continue today as subsidiaries of X-Rite, Inc. (<https://www.xrite.com>) [63].

3.12.2 Supporting CMYK Color Printing

As we noted in Section 3.1 of this chapter, the transfer between RGB and CMYK color spaces is far from perfect. Colors in the RGB space lose some of their vibrancy when transferred to the CMYK space. To address some of these concerns, it is possible to add inks that match the original colors in the RGB space to the printing process. This is a frequent use of PMS colors. Designers select colors and note their PMS values for the various stages of the CMYK color printing and reproduction effort. It is important to note that most Pantone colors cannot be reproduced by standard CMYK printing. The Pantone inks are added during the color printing process. The Pantone solution is thus more expensive than a typical CMYK printing process. The Adobe Color app (<http://www.adobe.com>) provides CMYK values for the four-color printing process, as well as Pantone colors for the more expensive PMS process. In Figure 3.29, an example of the Pantone ink selection process is shown using the freely available Adobe Color app.

3.12.3 Applying Color Theory Concepts with the Pantone Connect App

As mentioned earlier in this section, the Pantone Connect app is both a Web and a mobile application [64]. It is available online at the Pantone website and from Apple's App Store, Google Play, and Adobe Exchange. Pantone asks that you create a Pantone Connect account, but this can be derived from your Google or Facebook accounts if you have them. The app is free at a very basic level for searching the Pantone libraries of over 15,000 or more colors. A premium annual subscription of \$89.99 or a premium monthly subscription of \$14.99 provides access to the complete library of Pantone colors, data values, color harmonies, and references. More information on purchasing the Pantone Connect app is online at <https://connect.pantone.com/#/paywall>.

Tapping on a swatch displays the color in a detailed view. A selected Pantone color can be dragged into the palette zone to store it. With the Pantone color in the palette zone, tapping on it reveals the sRGB, hex codes, and Lab (CIE Lab) color data. In Figure 3.30,

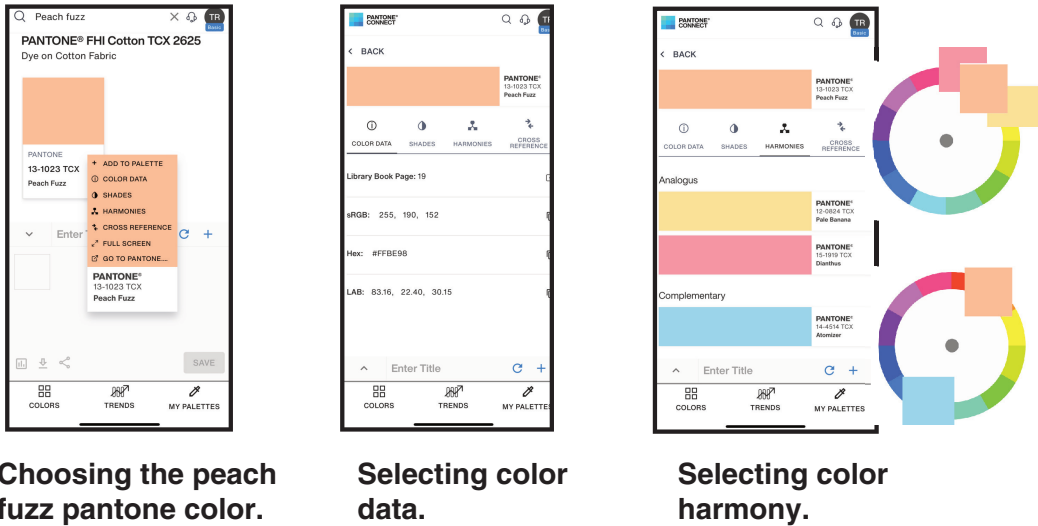


FIGURE 3.30 Using Pantone Connect to view the Peach Fuzz color, its corresponding color data, and harmonies. Pantone Connect does not provide a color wheel to explain the analogous and complementary harmonies, so we have added this annotation to the illustration. Analogous colors are adjacent to each other, while complementary colors directly oppose each other on the color wheel. Source: illustration by Theresa-Marie Rhyne, 2024, using the Pantone Connect app with color wheel annotations added.

we selected the Peach Fuzz hue from the array of Pantone colors. The sRGB values are 255, 190, and 152. The color hex code is #FFBE98. The Lab values are 83.16, 22.40, and 30.15. We have covered the sRGB color space in Section 3.3, hex triplets in Section 3.11.1, and the CIE Lab color space in Section 3.6.2 of this chapter.

3.12.4 Color Harmony with Pantone Connect

The Pantone Connect app also provides a harmony option for a selected Pantone color. Figure 3.30 also shows the analogous and complementary Pantone colors for Peach Fuzz. Color harmonies are determined by placement of colors on a color wheel. Colors that are adjacent to each other define an analogous color harmony. Colors that oppose each other on the color wheel define a complementary color harmony. For *Peach Fuzz*, Pantone Connect specifies *Pale Banana* and *Dianthus* as an analogous pair. The complementary color to *Peach Fuzz* is noted as *Atomizer*. Unfortunately, Pantone Connect does not provide a color wheel as a reference for these harmonies. We have added these annotations to Figure 3.30 to help clarify the information. We will cover color harmony in Chapter 4 and explore the Pantone Connect app further in Chapter 6.

3.13 CONCLUDING REMARKS

In this chapter, we reviewed the concepts of color gamut, color spaces, and color systems. The color spaces reviewed in this chapter are used widely in color reproduction and color standards. This chapter has provided the terminology to understand online and mobile

color apps that allow for digital color selection and capture. It is important to continue to remember a key concept about color gamut. Viewing a color in digital or virtual color space does not always mean that the color will appear the same in printed or physical color spaces. This is because of the differences in the RGB color model for display, the CMYK color model for printing, and the RYB color model for painting we highlighted in Chapters 1 and 2. In Chapter 4, we will examine concepts of color harmony that pertain in all three of these color models.

REFERENCES

1. Ibraheem, N.A., Hasan, M., Khan, R.Z., and Mishra, P.K. (2012), Understanding color models: A review. *ARPN Journal of Science and Technology*, 2 (3), 265–275.
2. Schanda, J., ed. (2007), *Colorimetry: Understanding the CIE System*, Hoboken, NJ: John Wiley & Sons.
3. Susstrunk, S., Buckley, R., and Swen, S. (1999), “Standard RGB color spaces.” In *Proc. IS&T/SID Seventh Color Imaging Conference*, 7, 127–134. US&T, 1999. ISBN: 0-89208-224-0.
4. Schewe, J.L., and Fraser, B. (2010), *Real World Camera Raw with Adobe Photoshop CSS*, Hoboken, NJ, Peachpit Press.
5. Hoffman, N. (2011), “2011 Color and Imaging Conference, Part VI: Special Session on Revisiting Color Spaces”, Real Time Rendering Blog, <https://www.realtimerendering.com/blog/2011-color-and-imaging-conference-part-vi-special-session/>. accessed September 20, 2024.
6. Stone, M. (2003) “Chapter 1 - Color vision”, *A Field Guide to Digital Color*, 1–19. Canada: A.K. Peters/CRC Press.
7. Fairman, H.S., Brill, M.H., and Hemmendinger, H. (1997), How the CIE 1931 color-matching functions were derived from Wright-Guild data. *Color Research and Application*, 22 (1), 11–27.
8. Wright, W.D. (2007), “Professor Wright’s paper from the golden jubilee book: The historical and experimental background to the 1931 CIE system of colorimetry”, *Colorimetry: Understanding the CIE System*, J Schanda, ed., 9–23. Hoboken, NJ: John Wiley & Sons.
9. MacAdam, D. L. (1942), Visual sensitivities to color differences in daylight. *Journal of the Optical Society of America*, 32 (5), 247–274.
10. Sharma, G. (2002), “Color fundamentals for digital imaging”, *Digital Color Imaging Handbook*, 2–97. Boca Raton, FL: CRC Press.
11. Sharma, G. and Bala, R., eds. (2002), *Digital Color Imaging Handbook*, Boca Raton, FL: CRC Press.
12. Ohta, N. (1977), Correspondence between CIELAB and CIELUV color differences. *Color Research and Application*, 2 (4), 178–182.
13. Olean, C. (2001), Comparisons between color-space scales, uniform-color-scale atlases, and color-difference formulae, *Color Research and Application*, 26 (5), 351–361.
14. Adams, E.Q. (1942), X-Z planes in the 1931 I.C.I. system of colorimetry, *Journal of Optical Society of America*, 32 (3), 168–173.
15. Nickerson, D. and Stultz, K.F. (1944), Color tolerance specification. *Journal of the Optical Society of America*, 34 (9), 550–570.
16. Hunt, R.W.G and Pointer, M.R. (2011), *Measuring Color*, 4th ed., Chichester, United Kingdom: John Wiley & Sons Ltd.
17. Hunter Labs (1996). Hunter lab color scale, *Applications Note*, 8 (9), 1–4.
18. Hunter Labs (2012), “Measuring Color Using Hunter L, a, b versus CIE 1976 L*a*b*”, <https://support.hunterlab.com/hc/en-us/articles/204137825-Measuring-Color-using-Hunter-L-a-b-versus-CIE-1976-L-a-b-AN-1005b>, accessed February 15, 2024.
19. Luo, M.R. and Hunt, R.W.G. (1998), The structure of the CIE 1997 colour appearance model (CIECAM97s). *Color Research and Application*, 23, 138–146.

20. Moroney, N., Fairchild, M., Hunt, R., and Li, C. (2002), “The CIECAM02 color appearance model”, *Proceedings of the IS&T/SID Tenth Color Imaging Conference*, Scottsdale, AZ, 23–27, <https://repository.rit.edu/cgi/viewcontent.cgi?article=1146&context=other>, accessed February 15, 2024.
21. Li, C., Li, Z., Wang, Z., Xu, Y., Lou, M.R., Cui, G., Melgosa, M., Brill, M.H., and Pointer, M. (2017), Comprehensive color solutions: CAM 16, CAT16, and CAM 16-UCS. *Color Research and Application*, 42, 703–718.
22. Ottosson, B. (2020), “A Perceptual Color Space for Image Processing”, Blog, <https://bottosson.github.io/posts/oklab/>, accessed February 16, 2024.
23. World Wide Web Consortium (2024), “9.2 Oklab and Oklch”, CSS Color Module Level 4, part of the W3C’s standards web site, <https://www.w3.org/TR/css-color-4/#ok-lab>, accessed February 16, 2024.
24. Munsell Color (2024), “Munsell Books of Color”, X-Rite Inc, <https://munsell.com/color-products/colorcommunications-products/munsell-books-and-sheets/>, accessed February 15, 2024.
25. Munsell, A.H. (1905), *A Color Notation*, Boston, MA: G.H. Ellis Company.
26. Munsell, A.H. (1915), *Atlas of the Munsell Color System*, Malden, MA: Wadsworth, Howland & Co., Inc.
27. Cleland, T.M., Munsell, A.H., and Strathmore Paper Company (1921), *A Grammar of Color: Arrangements of Strathmore Papers in a Variety of Printed Color Combinations According to the Munsell Color System*, Mittineague, MA: Strathmore Paper Co.
28. Nickerson, D. (1976), History of the Munsell Color System, Company, and Foundation. I. *Color Research and Application*, 1 (3), 7–10.
29. Nickerson, D. (1976), History of the Munsell Color System, Company and Foundation. II. Its scientific application. *Color Research and Application*, 1 (2), 69–77.
30. Nickerson, D. (1976), History of the Munsell Color System, Company and Foundation. III. *Color Research and Application*, 1 (3), 121–130.
31. Kuehni, R.G. (2002), The early development of the Munsell system, *Color Research and Application*, 27 (1), 20–27.
32. Landa, E.R. and Fairchild, M.D. (2005), Charting color from the eye of the beholder. *American Scientist*, 93 (5), 436–443. doi:10.1511/2005.5.436.
33. MacEvoy, B. (2005), “Modern Color Models – Munsell Color System”, Color Vision, part of the Handprint.com web site, <https://www.handprint.com/HP/WCL/color7.html#MUNSELL>, accessed February 17, 2024.
34. American Society of Testing Materials (1968), “ASTM D1535: Specifying Color by the Munsell System”, <https://archive.org/details/gov.law.astm.d1535.1968>, accessed February 17, 2024.
35. Munsell Color Company (2023), “Defining Color Systems for Precise Color Validation”, X-Rite Inc., https://www.xrite.com/-/media/xrite/files/literature/l10/l10-300_l10-399/l10-315_munsell_defining_color_multipage_brochure/l10-315_munsell_defining_color_en.pdf, accessed February 17, 2024.
36. Indow, T. and Aoki, N. (1983), Multidimensional mapping of 178 munsell colors. *Color Research and Application*, 8 (3), 145–152.
37. Briggs, D. (2007), “The Dimensions of Colour – The Dimension of Chroma”, Color Vision, part of the HueValueChroma web site, <http://www.huevaluechroma.com/082.php>, accessed August 24, 2024.
38. Munsell Color Science Laboratory (2024), “Munsell Renotation Data, Chester F. Carlson Center for Imaging Science at the Rochester Institute of Technology”, <https://www.rit.edu/science/munsell-color-science-lab-educational-resources#munsell-renotation-data>, accessed February 17, 2024.
39. WallkillColor (2024), “Munsell Conversion Software”, <http://wallkillcolor.com>, accessed August 24, 2024.

40. Werth, A. (2024), “Virtual Munsell Color Wheel”, <https://www.andrewwerth.com/about-munsell/>, accessed February 18, 2024.
41. Shoup, R. (2001), SuperPaint: An early frame buffer graphics system. *IEEE Annals of the History of Computing*, 23 (2), 32–37.
42. Smith, A.R. (1978), “color gamut transform pairs.” In *SIGGRAPH '78 Proceedings of the 5th Annual Conference on Computer Graphics and Interactive Techniques*, 12–19. New York: ACM.
43. Joblove, G.H. and Greenberg, D. (1978), “Color spaces for computer graphics.” In *SIGGRAPH '78 Proceedings of the 5th Annual Conference on Computer Graphics and Interactive Techniques*, 20–25, New York: ACM.
44. Hughes, J.F., Van Dam, A., McGuire, Morgan, S., David, F., Foley, J.D., Feiner, S.K., and Akeley, K. (2013), *Computer Graphics: Principles and Practice*, 3rd ed., Boston, MA: Addison-Wesley Professional.
45. Shepherd, E. T., Ivanica, G., and the Mozilla Development Network (2015 & 2023), “Color Picker Tool”, https://developer.mozilla.org/en-US/docs/Web/CSS/CSS_Colors/Color_picker_tool, accessed February 19, 2024.
46. Brown, T. F. (2016), “Colorpicker for Data”, <https://tristen.ca/hcl-picker/#/hlc/6/1/15534C/E2E062>, accessed February 21, 2024.
47. Zeileis, A., Fisher, J.C., Hornik, K., Ihaka, R., McWhite, C.D., Murrell, P., Stauffer, R., and Wilke, C.O. (2020), Colorspace: A toolbox for manipulating and assessing colors and palettes. *Journal of Statistical Software*, 96 (1), 1–49. arXiv#:1903.06490.
48. Coblindor (2021), “Coblis – Color Blindness Simulator”, <https://www.color-blindness.com/coblis-color-blindness-simulator/>, accessed February 23, 2024.
49. Levien, R. (2021), “An Interactive Review of Oklab”, <https://raphlinus.github.io/color/2021/01/18/oklab-critique.html>, accessed February 22, 2024.
50. World Wide Web Consortium (2024), “Web Standards”, part of the W3C’s standards web site, <https://www.w3.org/standards/>, accessed February 24, 2024.
51. Atkins Jr, T., Lilley, C., Verou, and the World Wide Web Consortium (2024), “Section 4: Representing Colors: The Color Type in CSS Color Module Level 4”, <https://www.w3.org/TR/css-color-4/#color-type>, accessed February 24, 2024.
52. Bellamy-Royds, A. and Cagle, K. (2015), *SVG Colors, Patterns & Gradients: Painting Vector Graphics*, Sebastopol, CA: O’Reilly Media.
53. Cloford.com (2015), “Web-Safe Colours”, <https://cloford.com/resources/colours/websafe1.htm>, accessed February 24, 2024.
54. HTMLCOLOR CODES (2023), “Web Safe Color Chart”, <https://htmlcolorcodes.com/color-chart/web-safe-color-chart/>, accessed February 24, 2024.
55. Goode, L. (2023), “Review: We Put ChatGPT, Bing Chat, and Bard to the Test”, Wired Magazine, March 30, 2023, <https://www.wired.com/story/review-ai-chatbots-bing-bard-chat-gpt/>, accessed February 24, 2024.
56. Open AI (2024), “ChatGPT 3.5”, <https://chat.openai.com>, accessed February 26, 2024.
57. Adobe Inc. (2024), “Color Palette Generator | Adobe Color”, <https://color.adobe.com>, accessed February 24, 2024.
58. Digital Media Interactive LLC (2018), “Color Companion – Analyzer & Converter”, <https://itunes.apple.com/us/app/color-companion-analyzer-converter/id477794973?mt=8>, accessed February 26, 2024.
59. Pantone (2024), “The Pantone Matching System”, <https://www.pantone.com/the-pantone-matching-system>, accessed February 27, 2024.
60. Harzen (2024), “Pantone Colours”, <https://www.pantone-colours.com/>, accessed February 27, 2024.
61. Budds, D., “How Pantone Became the Definite Language of Color”, Fast Company, September 18, 2015, <https://www.fastcompany.com/3050240/how-pantone-became-the-definitive-language-of-color>, accessed February 28, 2024.

62. Stevenson, S., “Who Put Pantone in Charge of Color?”, Slate, March 01, 2021, <https://slate.com/business/2021/03/what-is-pantone-color-of-the-year.html>, accessed February 28, 2024.
63. X- Rite (2024) “About X-Rite Pantone”, <https://www.xrite.com/page/our-brands>, accessed February 28, 2024.
64. Pantone (2024), “Pantone Connect”, <https://connect.pantone.com/>, accessed February 29, 2024.

Defining Color Harmony

4.1 THE COLOR WHEEL

Color wheels are tools that depict color relationships by organizing colors in a circle to visualize how the hues relate to each other. Many color wheels are based on three primary colors and three secondary colors and the six intermediate or tertiary colors formed by mixing a primary with a secondary color. This results in 12 hues on the color wheel. Some color wheels have even finer divisions resulting in 24 colors being depicted. The primary colors are the core of a color model and cannot be mixed. The secondary colors are mixtures of the primary colors. Figure 3.16 in Chapter 3 depicts colors associated with the hue, saturation, and value and hue, saturation, and lightness color spaces and is a typical example of the configuration of 12 hues. Other color wheel examples include four opponent colors and can have four or eight main colors. Figure 2.4 in Chapter 2 that diagrammed Ewald Hering's opponent color theory is an example of a color wheel with four main colors. The Munsell color order system includes five primary hues and five secondary hues. We diagrammed the Munsell hue circle with a total of 40 hue divisions in Figure 3.12 of Chapter 3. In this chapter, we look further into the steps of constructing a color wheel, examine the color harmony between hues on the wheel, and highlight some historical and current evolutions of the color wheel such as color gamut masking. References [1–4] provide additional reading on the principles of color harmony.

4.2 THE STEPS IN CONSTRUCTING A COLOR WHEEL

There are four steps in constructing a color wheel: (1) define the color model and place the resulting primaries equidistantly on the wheel; (2) determine the resulting secondary colors that are mixtures of the primary colors and place the secondary colors equidistantly between the primaries on the wheel; (3) establish the tertiary colors that are mixtures of primary and secondary hues and place the tertiary colors equidistantly between the primary and secondary colors; and (4) refine the color wheel with additional equidistant divisions and neutral colors if desired. We work through these four steps for the three-color models we defined in Chapter 1: (1) the Red, Green, and Blue (RGB) display

color model; (2) the Cyan, Magenta, and Yellow (CMYK) printers color model; and (3) the Red, Yellow, and Blue (RYB) painters color model.

4.2.1 Geometry of the RGB Display Color Wheel

Step 1 is easily determined for the RGB display model with the primary colors being Red, Green, and Blue. We place these three colors clockwise and equidistantly from each other. We learned step 2 in Chapter 1 with the secondary colors being the combination of Red and Green to equal Yellow, Green and Blue to equal Cyan, and Blue and Red to equal Magenta. We place these secondary colors clockwise and equidistantly between the primary RGB colors. For step 3, the tertiary colors are Red-Yellow (Orange), Yellow-Green (Lime), Green-Cyan (Aqua Marine), Cyan-Blue (Deep Sky Blue), Blue-Magenta (Purple), and Magenta-Red (Deep Pink). We place these tertiary colors in clockwise respective locations on the wheel between the primary and secondary colors. For step 4 neutral, Gray is the combination of two colors opposing one another on the wheel such as Red and Cyan. So, we place Gray in the center. We show these steps in Figure 4.1.

4.2.2 Geometry of the CMYK Printers Color Wheel

The geometry of the CMYK printers color wheel is the inverse of the RGB display color wheel. For step 1, the primary colors are Cyan, Magenta, and Yellow. We place these three colors clockwise and equidistantly from each other. In step 2, the three secondary colors are the combination of Cyan and Magenta to equal Blue, the combination

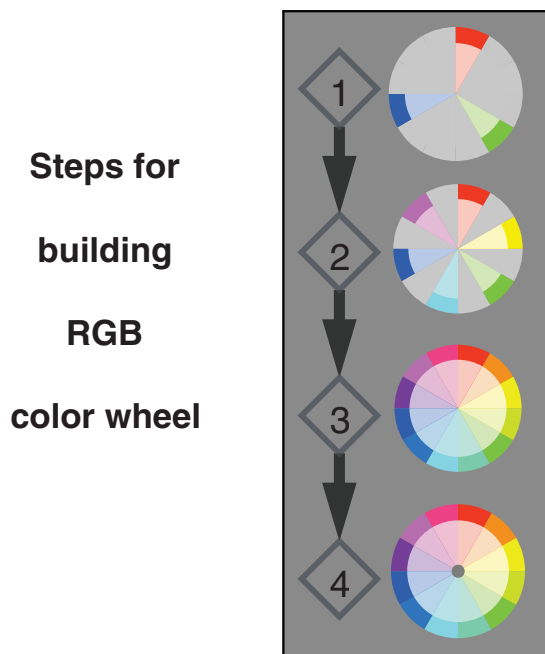


FIGURE 4.1 Steps for building the Red, Green, and Blue (RGB) color wheel. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

**Steps for
building
CMYK
color wheel**

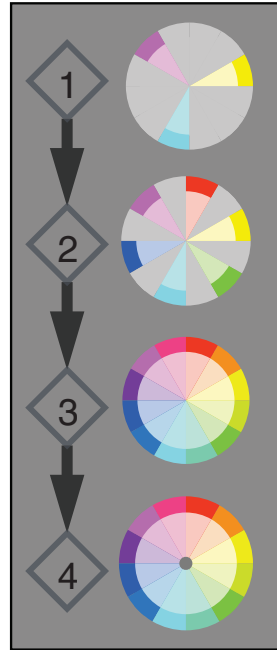


FIGURE 4.2 Steps for building the Cyan, Magenta, Yellow, and Key Black (CMYK) color wheel: Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

of Magenta and Yellow to yield Red, and the combination of Yellow and Cyan to equal Green. We place these secondary colors clockwise and equidistantly between the primary CMY colors. For step 3, the tertiary colors are Cyan-Blue (Deep Sky Blue), Blue-Magenta (Purple), Magenta-Red (Deep Pink), Red-Yellow (Orange), Yellow-Green (Lime), and Green-Cyan (Aqua Marine). We place these tertiary colors in clockwise respective locations on the wheel between the primary and secondary colors. For step 4, Gray is the combination of two colors opposing one another on the wheel such as Cyan and Red. So, we place Gray at the center of the circle. We show these steps in Figure 4.2.

4.2.3 Geometry of the RYB Painters Color Wheel

The RYB color wheel provides a guide to developing color palettes for art compositions. It is based on how artists have naturally combined paint color pigments for centuries with minerals from the earth. The RYB color wheel is frequently the first color wheel we learned in our own childhood education while mixing our paint colors. The RYB color palette has more earth tones to it than the RGB color palette created from lights and the CMYK color palette created from printing inks. For step 1 in building the RYB color wheel, the primary colors are Red, Yellow, and Blue. In step 2, the secondary colors are the combination of Red and Yellow to produce Orange, the combination of Yellow and Blue to produce Green, and the combination of Blue and Red to produce Purple. We place these secondary colors clockwise and equidistantly between the primary RYB colors. For step 3, the tertiary colors are Red-Orange, Orange-Yellow, Yellow-Green,

**Steps for
building
RYB
color wheel**

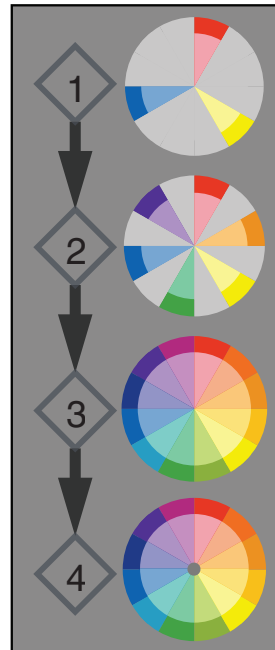


FIGURE 4.3 Steps for building the Red, Yellow, and Blue (RYB) color wheel. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Green-Blue, Blue-Purple, and Purple-Red. We place these tertiary colors in clockwise respective locations on the wheel between the primary and secondary colors. For step 4, as in our previous examples, Gray is the combination of two colors opposing one another on the wheel such as Red and Green. So, we place Gray in the center of the wheel. We show these steps in Figure 4.3.

4.2.4 Comparing the RGB, CMYK, and RYB Color Wheels

The RGB additive and the CMYK subtractive color wheels are composed of the same hues and are the inverse combinations of each other, as we noted in Chapter 1, Figure 1.6. So, one color wheel will suffice as we focus on defining color harmony concepts in the next sections of this chapter. For further discussion in this chapter, we will reference the RGB/CMYK color wheel. The RGB/CMYK and RYB color wheels differ in the hues for each respective color shown. Historically, many aspects of color theory were developed by artists and designers based on the RYB color wheel. We will highlight some of this evolution later in this chapter. As we noted in Chapter 1, the RYB subtractive color model is similar but different from either of the RGB and CMYK models. In applying color theory to digital media, it becomes helpful to understand both the RGB/CMYK and RYB color wheels for effective application and communication of color harmony. Figure 4.4 compares the RGB/CMYK and RYB color wheels side by side.

Comparison of RGB/CMYK and RYB color wheels

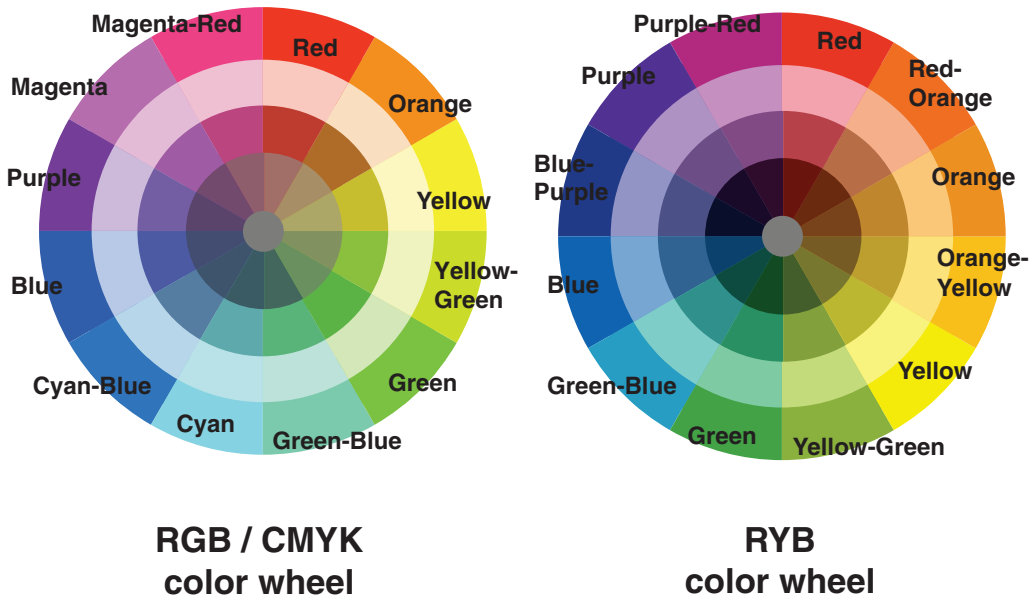


FIGURE 4.4 Comparison of RGB/CMYK and RYB color wheels. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

4.3 DEFINING HUES, TINTS, TONES, AND SHADES ON THE COLOR WHEEL

As we noted when reviewing color spaces in Chapter 3, a color is defined in terms of its specific parameters such as hue, value, and chroma in the Munsell color order systems or hue, saturation, and value in the HSV color space. For a detailed color wheel, there are four rings of concentric circles that represent the elements of *hues*, *tints*, *tones*, and *shades*. We define each of these elements below and visually summarize them in Figure 4.4.

4.3.1 Hues

As in the color spaces we discussed in Chapter 3, a *hue* is the brightest or purest form of a color and resides on the outermost part of the color wheel. In Figure 4.5, colors on the outer rim represented in the RGB/CMYK and the RYB wheels are the hues.

4.3.2 Tints

A *tint* is defined as a hue mixed with White. Tints can vary from small to large percentages of White mixed with the original hue. In Figure 4.6, the tints are shown as the second circle next to the hues of the RGB/CMYK and the RYB wheels. We used 50% hue and 50% White to form the tints shown in the wheels.

Hues of RGB/CMYK and RYB color wheels

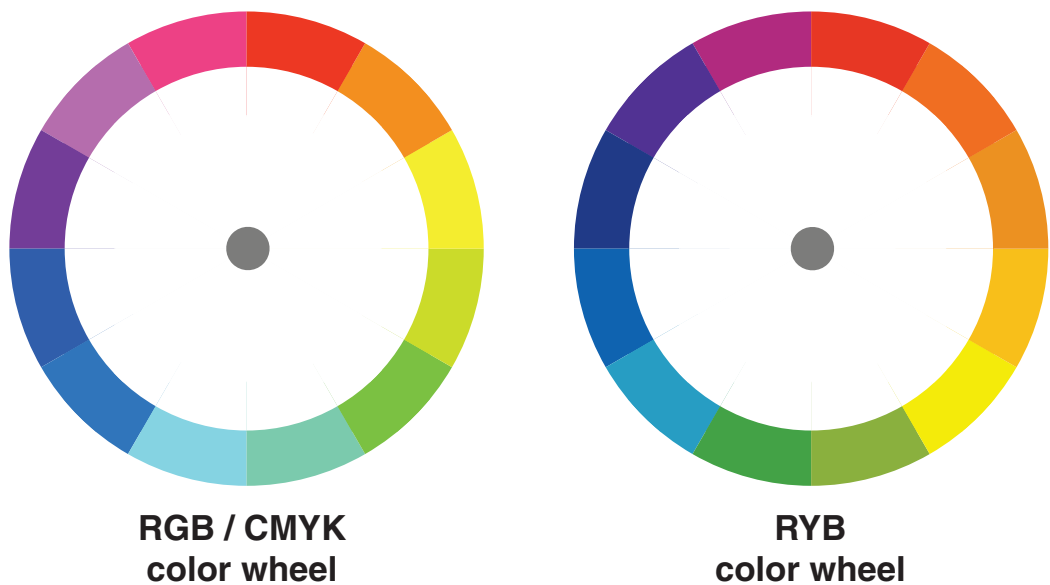


FIGURE 4.5 Hues on the RGB/CMYK and RYB color wheels. Hues are shown on the outer rim of the wheel and are the brightest and purest colors. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Tints of RGB/CMYK and RYB color wheels

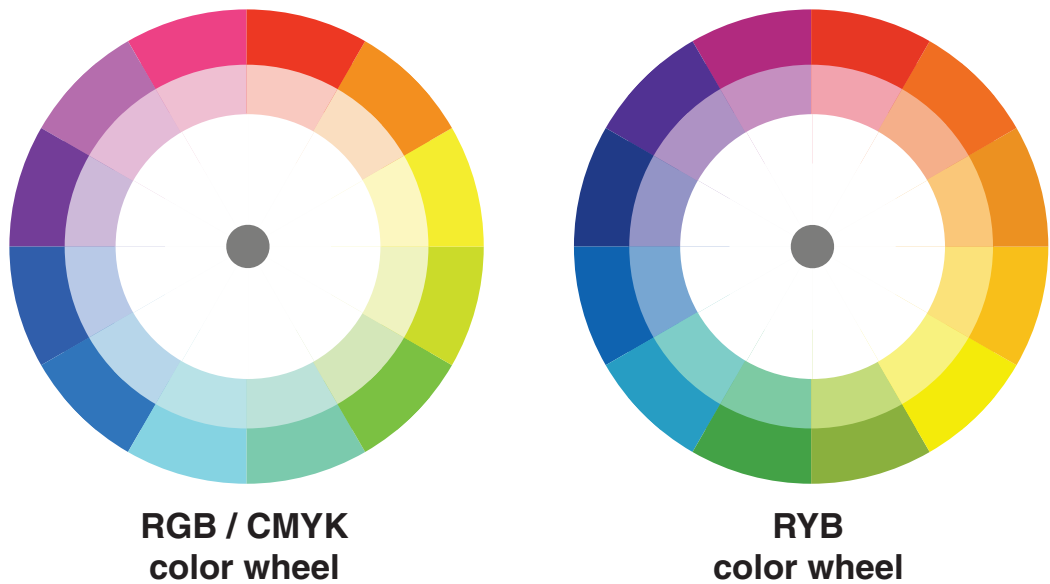


FIGURE 4.6 Tints on the RGB/CMYK and RYB color wheels. Tints are represented as the second circle next to the hues on the wheel. Tints are defined as a hue mixed with White. Source: image created by Theresa-Marie Rhyne, 2016 & 2024

Tones of RGB/CMYK and RYB color wheels

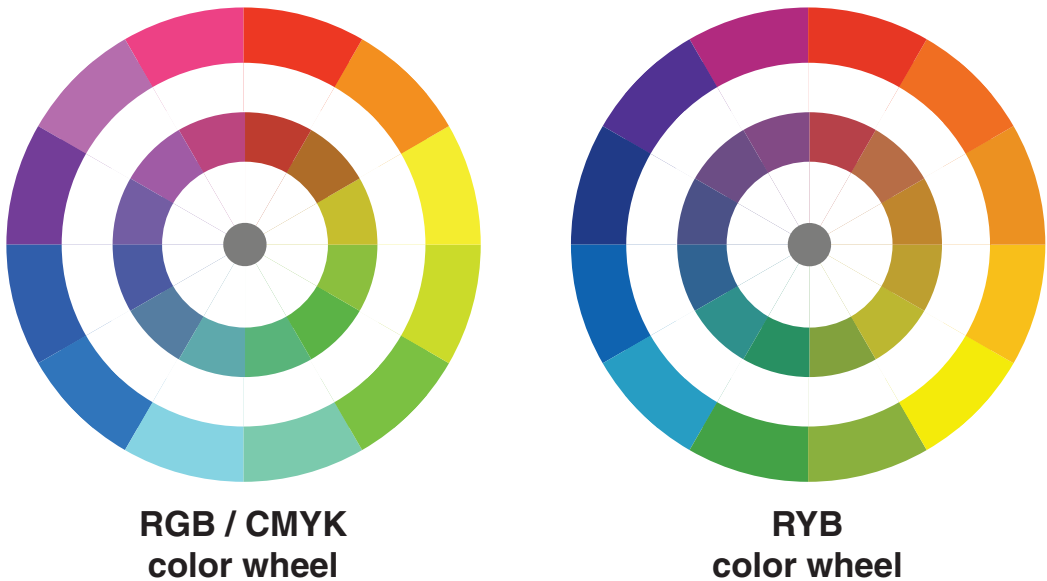


FIGURE 4.7 Tones on the RGB/CMYK and RYB color wheels. Tones of hues are represented as the third circle or ring on the wheel. Tones are defined as a hue mixed with Gray. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

4.3.3 Tones

A *tone* is a hue mixed with true Gray. A hue mixed with any amount of Gray is called a tone of the hue. In Figure 4.7, we show the tones as the third concentric ring of the RGB/CMYK and the RYB wheels. We used 50% hue and 50% Gray to form the tints shown in the wheels.

4.3.4 Shades

A *shade* is defined as a hue mixed with Black. Just as with tints and tones, a shade can vary from small to large percentages of Black mixed with the original hue. In Figure 4.8, the fourth and inner most concentric ring of the RGB/CMYK and the RYB wheels depicts shades of the various hues. We used 50% hue and 50% Black to form the tints shown in the wheels.

4.4 WARM AND COOL COLORS ON COLOR WHEELS

The colors on the color wheel can be divided into *warm and cool* colors. In general, Green, Blue, and Purple are defined as cool colors, while Yellow, Orange, and Red are grouped as warm colors. Warm colors tend to advance and expand in space. Cool colors tend to recede and contract in space. White, Gray, and Black are considered to be neutral in this regard. As a result, colors can have physiological and psychological effects on people. Wassily Kandinsky, in 1910, published detailed writings on these effects of color in his “Concerning the Spiritual in Art” essay [5]. Two colors can also have a relative color temperature with

Shades of RGB/CMYK and RYB color wheels

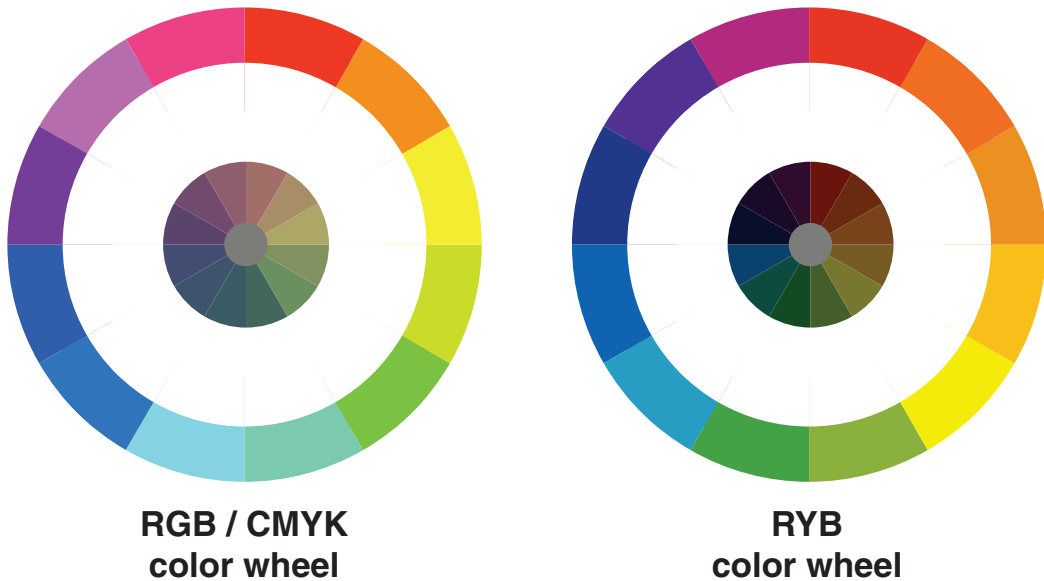


FIGURE 4.8 Shades on the RGB/CMYK and RYB color wheels. Shades of hues are represented as the innermost circle or ring on the wheel. Shades are defined as a hue mixed with Black. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

regard to one another. For example, on the RGB/CMYK color wheel, Magenta is considered a hotter color against its adjacent cooler Purple. In the RYB color space, a warm Red-Orange color can be used to project a crackling fire, while its Green-Blue complement can be used to project a calm sea breeze. In Figure 4.9, we show the division of warm and cool colors on the RGB/CMYK and RYB color wheels respectively.

4.5 COLOR HARMONY

Color harmony is the process of choosing colors that work well together in the composition of an image. Similar to concepts in music, there are “color cords” on the color wheel that help to provide common guidelines for how hues will work together. These color cords are generalized recommendations with the final color selection dependent on specific parameters associated with the design project. An important aspect in working with color harmony is determining a key color to build the harmonies around. We define basic cords on the color wheel that represent color harmony in the key hue of Yellow below.

For each harmony, we work through an example that applies these concepts. In our examples, we frequently work with the principles of hues, tints, tones, and shades to create variations in color selection. The examples shown here are basic infographic or information visualization charts that can be generated with software tools like Microsoft Excel or Word, Apple’s Numbers or Pages, Google Docs, Tableau Software, and many others. For our examples, we used the chart functions in Apple’s Numbers and Apple’s Pages. We use

Warm and cool colors on color wheels

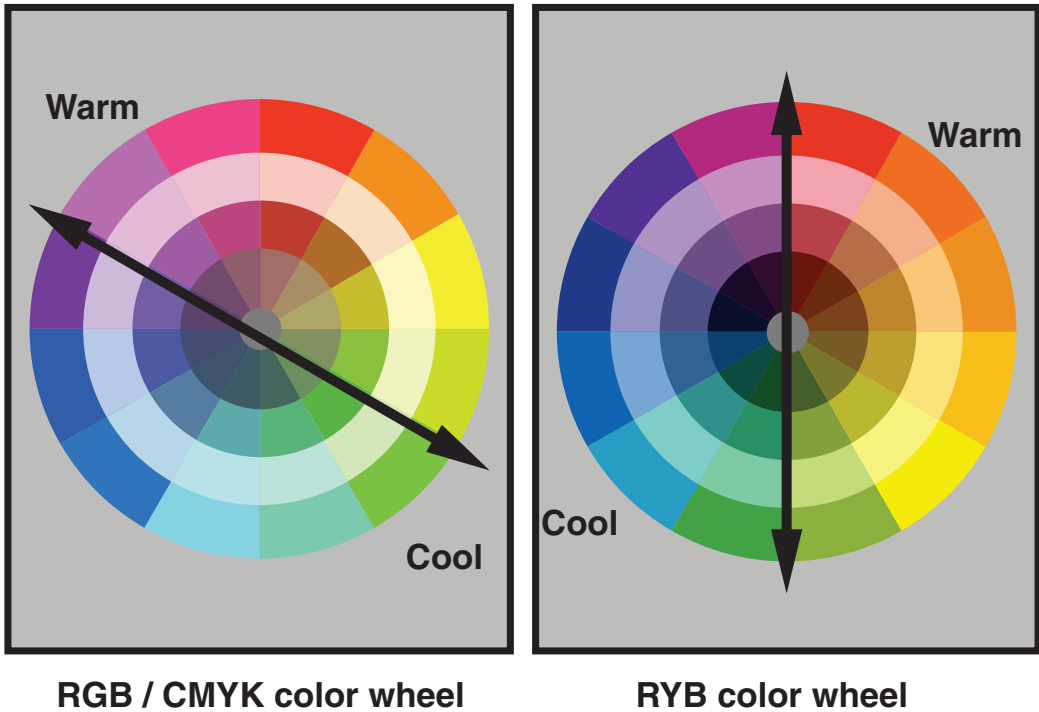


FIGURE 4.9 Division of warm and cool colors on the RGB/CMYK and RYB color wheels. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

a sample data set of sales over a four-month period. We apply color harmonies in the key of Yellow within the RGB/CMYK color space.

4.5.1 Monochromatic Harmony

Monochromatic harmony uses one hue and various tints, tones, and shades associated with that one hue. In Figure 4.10, we establish Yellow as our key color and include a tint, tone, and shade of the selected hue.

4.5.1.1 Example of Monochromatic Harmony

In this example, we develop a pie chart of sales data over four months and apply a monochromatic harmony in the key of Yellow. With monochromatic harmony, we use a single hue and its tints, tones, and shades to produce the color variance. Figure 4.11 shows our pie chart with Yellow monochromatic harmony.

4.5.2 Analogous Harmony

Analogous harmony is based on the concept of three colors that are next to each other on the color wheel. In Figure 4.12, we show analogous harmony with Yellow at the center for the RGB/CMYK and the RYB color wheels.

Monochromatic color harmony

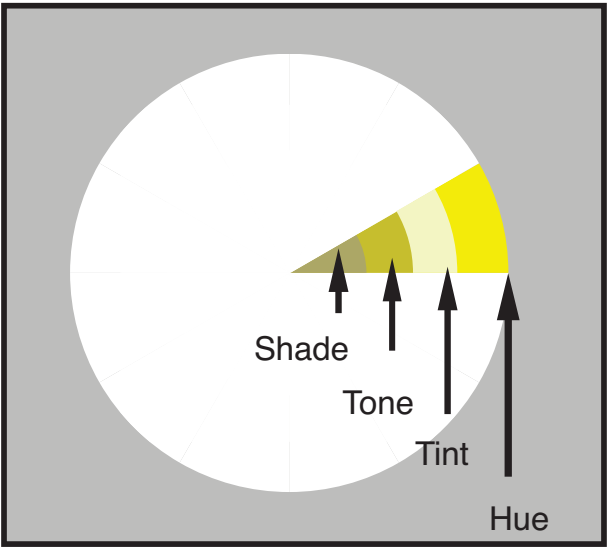


FIGURE 4.10 Monochromatic color harmony in the key of Yellow. Source: image created by Theresa-Marie Rhyne, 2016.

Example of monochromatic harmony

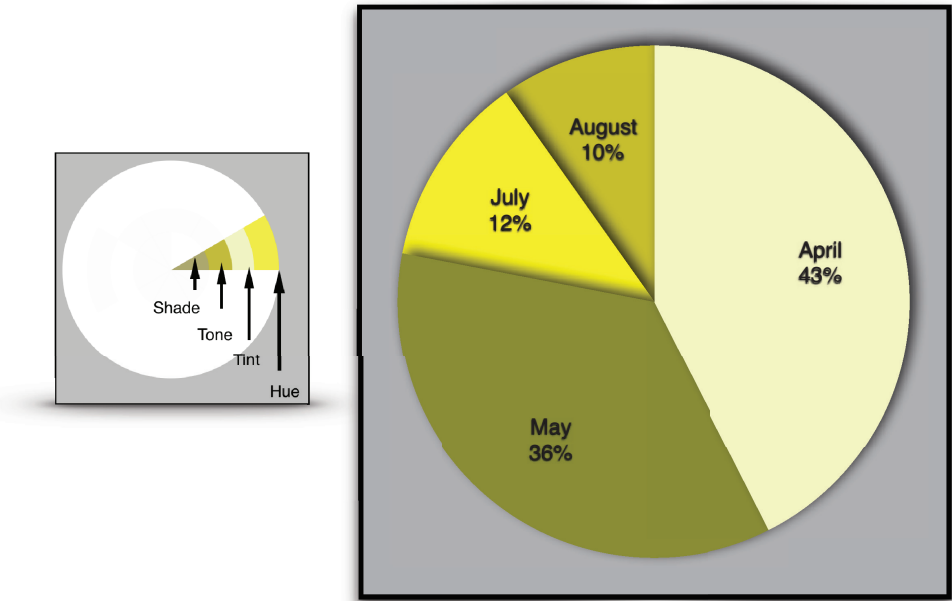


FIGURE 4.11 Example of the application of a monochromatic harmony to a pie chart visualization. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Analogous harmony for RGB/CMYK and RYB color wheels

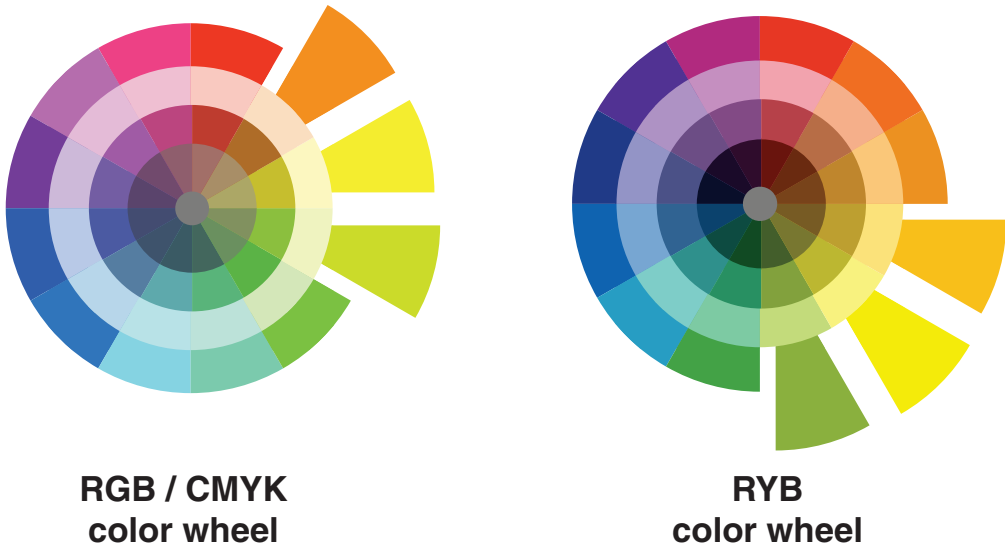


FIGURE 4.12 Analogous color harmony in the key of Yellow for the RGB/CMYK and RYB color wheels. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

4.5.2.1 Example of Analogous Harmony

Here, we develop a two-dimensional bar chart of sales data over four months and apply an analogous harmony in the key of Yellow. For this example, we select the Yellow hue, the Orange hue on its left, and the Yellow-Green hue on its right. We also use shades of each of the three colors. Figure 4.13 shows our two-dimensional bar chart with a Yellow analogous harmony that includes hues and shades of Orange, Yellow, and Yellow-Green colors.

4.5.3 Complementary Harmony

Complementary harmony represents colors that oppose or are across from each other on the color wheel. In the RGB/CMYK color space, the hue of Yellow is complementary to Blue. In the RYB color space, the hue of Yellow is complementary to Purple. In Figure 4.14, complementary harmony in the key hue of Yellow is depicted on both the RGB/CMYK and RYB color wheels.

4.5.3.1 Example of Complementary Harmony

We create a three-dimensional bar chart of sales data over four months and apply a complementary harmony in the key of Yellow. In the RGB/CMYK color space, Yellow opposes Blue on the color wheel and the two colors are complements. For our bar chart example, we use tones of the Yellow and Blue hues for plotting our three-dimensional bars. These results are shown in Figure 4.15.

Example of analogous harmony

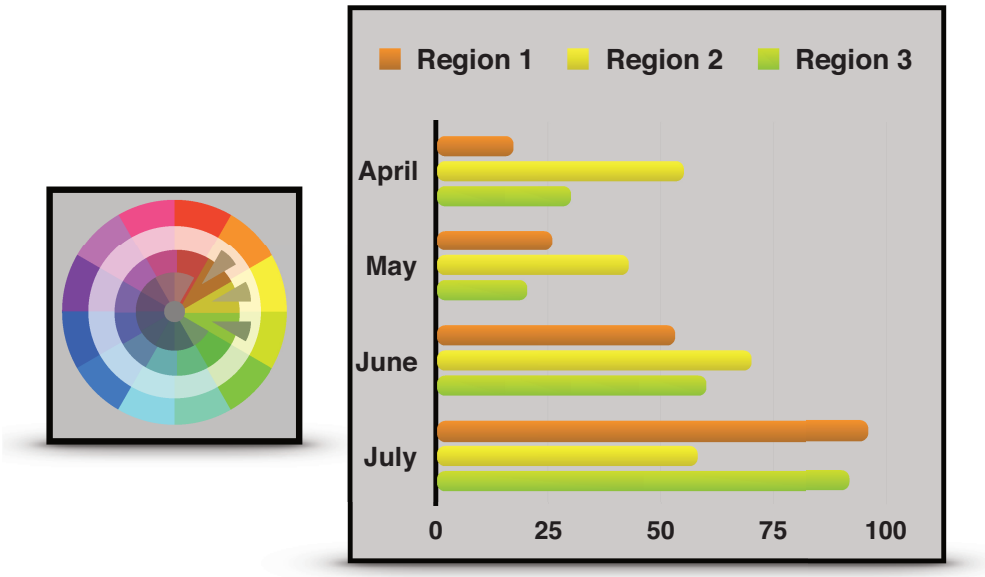


FIGURE 4.13 Example of an analogous harmony applied to a two-dimensional bar char visualization. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Complementary harmony for RGB/CMYK and RYB color wheels

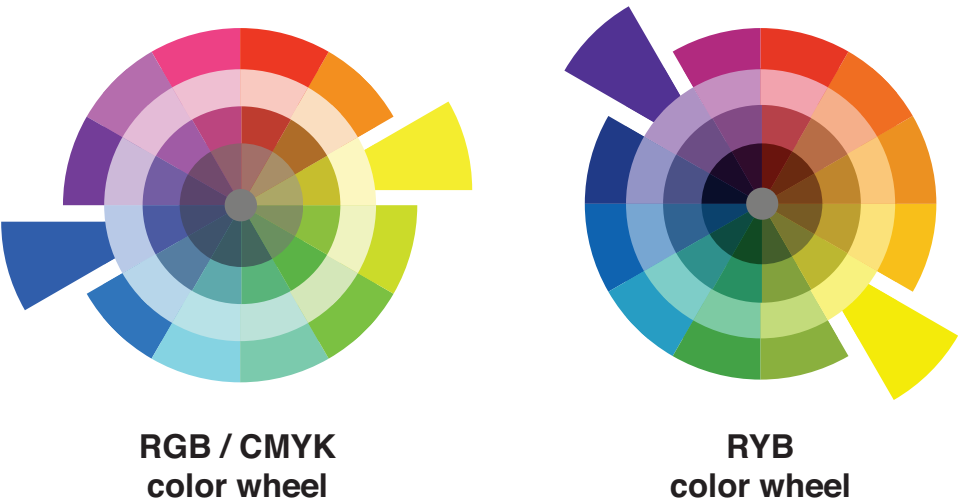


FIGURE 4.14 Complementary harmony in the key of Yellow for the RGB/CMYK and RYB color wheels. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Example of complementary harmony

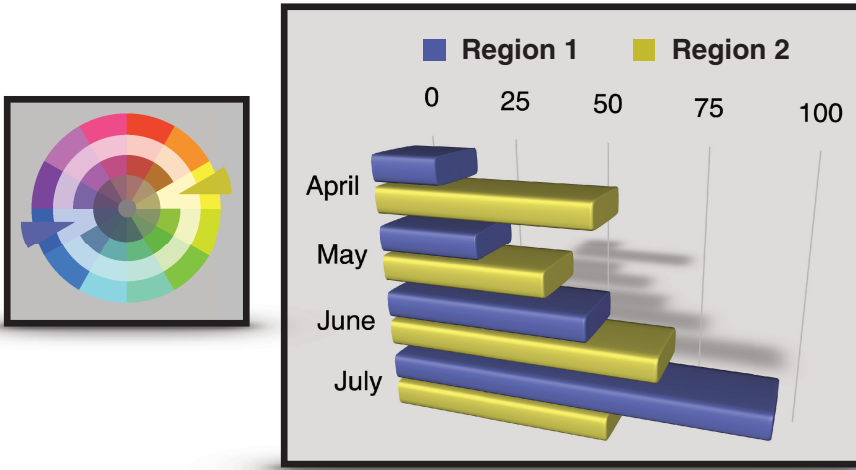


FIGURE 4.15 Example of complementary harmony applied to a three-dimensional bar chart visualization. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

4.5.4 Split Complementary Harmony

A *split complementary* harmony combines a key color with the two colors directly on either side of the complementary color. As we noted above, in the RGB/CMYK color space, the hue of Yellow is complementary to Blue. So, the split complementary hues are Cyan-Blue (Deep Sky Blue) and Blue-Magenta (Purple). In the RYB color space, the hue of Yellow is complementary to Purple. The resulting split complementary hues are Blue-Purple and Purple-Red. In Figure 4.16, split complementary harmony in the key hue of Yellow is shown for the RGB/CMYK and RYB color wheels.

4.5.4.1 Example of Split Complementary Harmony

We build a two-dimensional bar chart with a line plot of sales data over four months and apply a split complementary harmony in the key of Yellow. To create a split complementary harmony, we use the colors on either side of Blue and combine them with Yellow. In the RGB/CMYK color space, Yellow opposes Blue on the color wheel. The split complementary hues for Blue are Cyan-Blue (Deep Sky Blue) and Blue-Magenta (Purple). For our two-dimensional bar chart with a line plot example, we use solid hues of Yellow with Cyan-Blue and Blue-Magenta (Purple) to form the split complementary harmony. These results are shown in Figure 4.17.

4.5.5 Analogous Complementary Harmony

The *analogous complementary* harmony represents a key color combined with its direct complement and the two colors on either side of the complement. As noted in the split complementary harmony discussion, in the RGB/CMYK color space, the hue of Yellow is

Split complementary harmony for RGB/CMYK and RYB color wheels

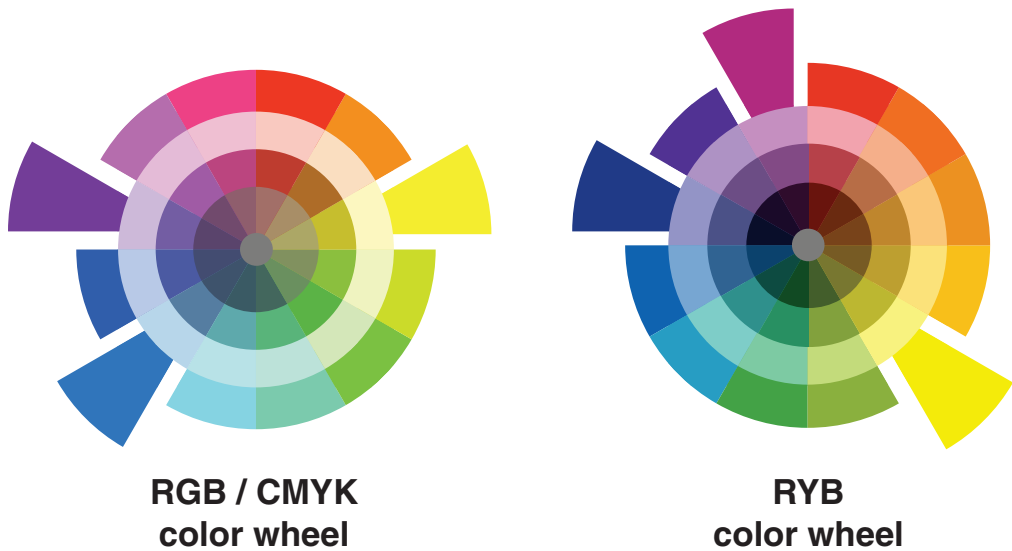


FIGURE 4.16 Split complementary color harmony in the key of Yellow for the RGB/CMYK and RYB color wheels. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Example of split complementary harmony

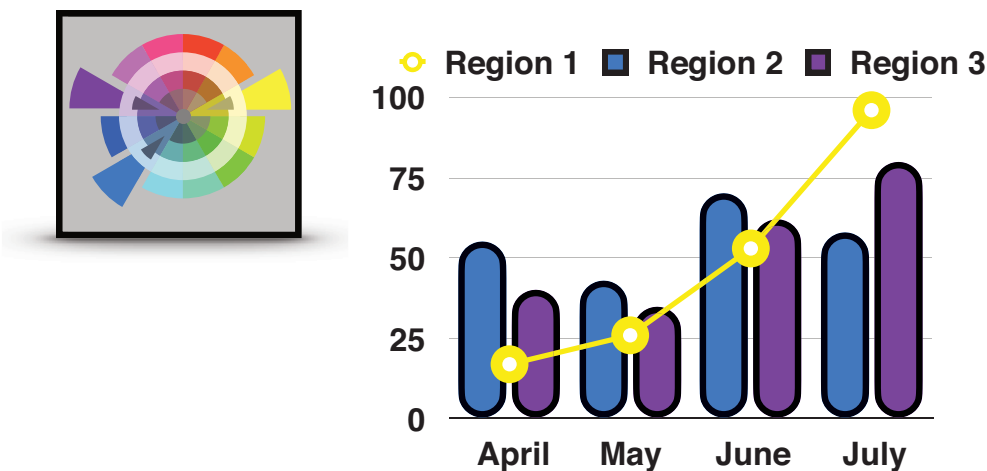


FIGURE 4.17 Example of split complementary harmony applied to a two-dimensional bar chart with a line plot visualization. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Analogous complementary harmony for RGB/CMYK and RYB color wheels

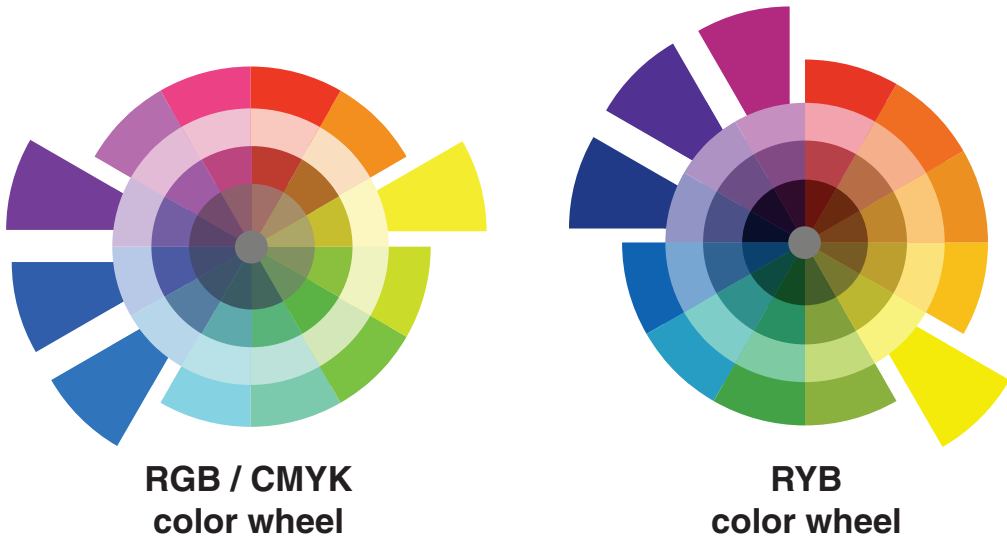


FIGURE 4.18 Analogous complementary color harmony in the key of Yellow for the RGB/CMYK and RYB color wheels. Source: Image created by Theresa-Marie Rhyne, 2016 & 2024.

complementary to Blue, and the split complementary hues are Cyan-Blue (Deep Sky Blue) and Blue-Magenta (Purple). So, the analogous complementary harmony in the key of Yellow combines Yellow with the three Blues that include Cyan-Blue, Blue, and Blue-Magenta. In the RYB color space, the hue of Yellow is complementary to Purple and the resulting split complementary hues are Blue-Purple and Purple-Red. The RYB analogous complementary harmony in the key of Yellow combines Yellow and the three Purples that encompass Blue-Purple, Purple, and Purple-Red. In Figure 4.18, analogous complementary harmony in the key hue of Yellow is shown for the RGB/CMYK and RYB color wheels.

4.5.5.1 Example of Analogous Complementary Harmony

In this example, a two-dimensional plot of sales data points for three months is shown with a trend line. We use an analogous complementary harmony in the key of Yellow for this plot. The trend line is shown with the Yellow hue. The hues with Blue at the center, Purple (Blue-Magenta) to the right of Blue, and Cyan-Blue to the left of Blue form the colors for the points of the three months of sales data. As the RGB/CMYK color wheel shows, this is an analogous complementary harmony. The Yellow hue is directly complementary to the three analogous colors of Purple, Blue, and Cyan-Blue. To address potential color deficiency issues, as noted in Section 2.8 of Chapter 2, the Purple data set is represented as *rectangles*, the Blue data set is represented as *triangles*, and the Cyan-Blue data set is represented as *circles*. The viewer can differentiate these data elements according to the color and geometry.

Example of analogous complementary harmony

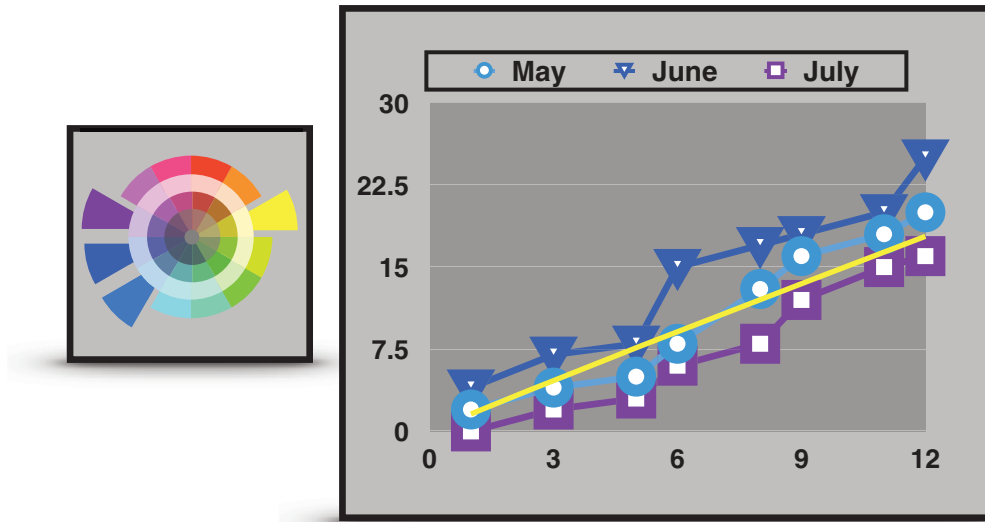


FIGURE 4.19 Example of analogous complementary harmony applied to a plot of data points with a trend line of sales data for 3 months. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Notice that the addition of a White center to the three hues of the points in the plot, as well as the use of a Darker Gray background for the graph space, changes the overall intensity of our four colors. This is an example of the concepts that Josef Albers wrote about in his book entitled *Interaction of Color* [6]. We discuss Josef Albers later in this chapter. These results are shown in Figure 4.19.

4.5.6 Double Complementary Harmony

The *double complementary* harmony includes two sets of complementary colors that are next to each other and across from each other on the color wheel. For our example, we include the key hue of Yellow with its adjacent color of Orange in the RGB/CMYK color space. This results in Yellow and Orange combining with their respective complements of Blue and Cyan-Blue (Deep Sky Blue). In the RYB color space, we show the key hue of Yellow with its adjacent color of Orange-Yellow. This results in Yellow and Orange-Yellow combining with their respective complements of Purple and Blue-Purple. The two complementary pairs crossing each other form an X pattern on the color wheel. In Figure 4.20, double complementary harmony in the key hue of Yellow and adjacent Orange for the RGB/CMYK color wheel and double complementary harmony in the key hue of Yellow and adjacent Orange-Yellow for the RYB color wheel are shown.

4.5.6.1 Example of Double Complementary Harmony

Here, we build a stacked two-dimensional bar chart for sales data during a four-month time frame. The stacked bar chart allows us to display the contribution of each of the

Double complementary harmony for RGB/CMYK and RYB color wheels

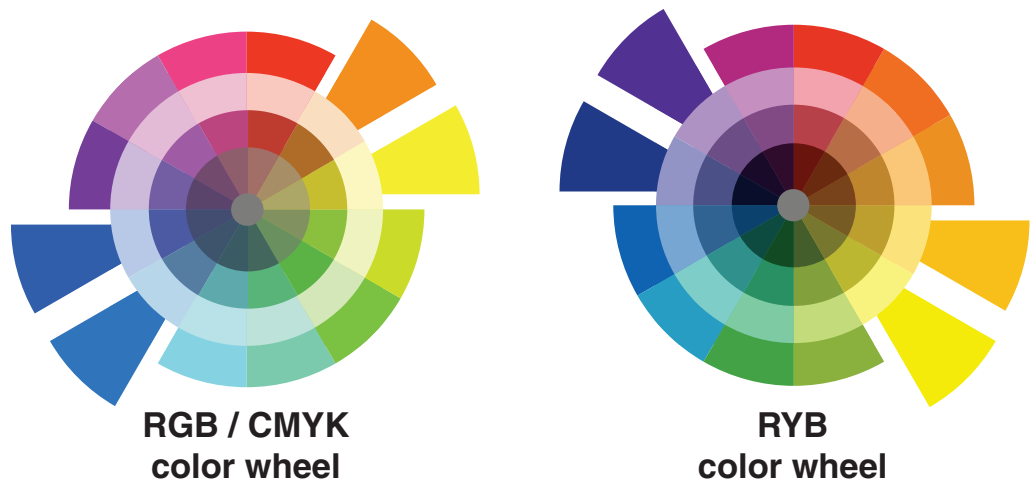


FIGURE 4.20 Double complementary color harmony in the key of Yellow for the RGB/CMYK and RYB color wheels. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

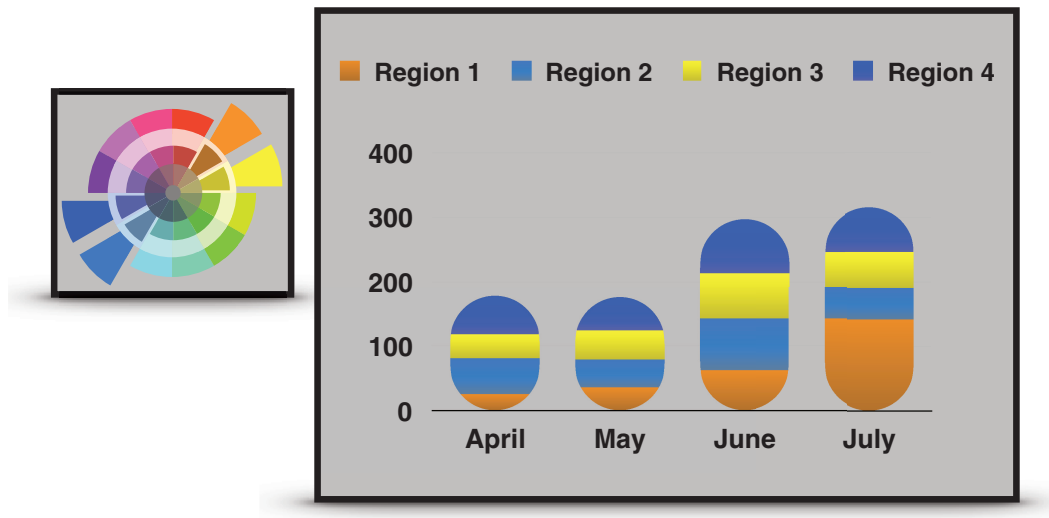


FIGURE 4.21 Example of double complementary harmony in the key of Yellow applied to a stacked two-dimensional bar chart. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

four regions. For our colors, working in the RGB/CMYK color space, we select a double complementary harmony in the key of Yellow. For our example, Yellow and Orange hues and tones are combined with respective hues and tones of their corresponding complements Blue and Cyan-Blue. We show these results in Figure 4.21.

4.5.7 Tetrad Harmony

The *tetrad* harmony includes four hues that are equally distant from one another to form a rectangle or square on the color wheel. The result is two complementary pairs but spaced at least two steps apart for rectangular harmony and three steps apart for square harmony. We show an example of each in the key hue of Yellow below.

4.5.7.1 Rectangular Harmony

With a *rectangular* harmony, four hues are equally distant and form a rectangle on the color wheel. The result combines two pairs of complementary colors that are two steps apart on the color wheel. For our example, the key hue of Yellow and its Blue complement are two steps from Green and its Magenta complement on the RGB/CMYK color wheel, while Yellow and its Purple complement are two steps from Green and its complement Red on the RYB color wheel. Figure 4.22 visually illustrates this concept.

4.5.7.1.1 Example of Tetrad – Rectangular Harmony

In this example, we work with a rectangular harmony in the key of Yellow to colorize a horizontal two-dimensional stacked bar chart of sales data in four regions over a time frame of four months. To begin the rectangular harmony, we require two colors that are two steps from each other on the RGB/CMYK color wheel. Yellow and Green meet this

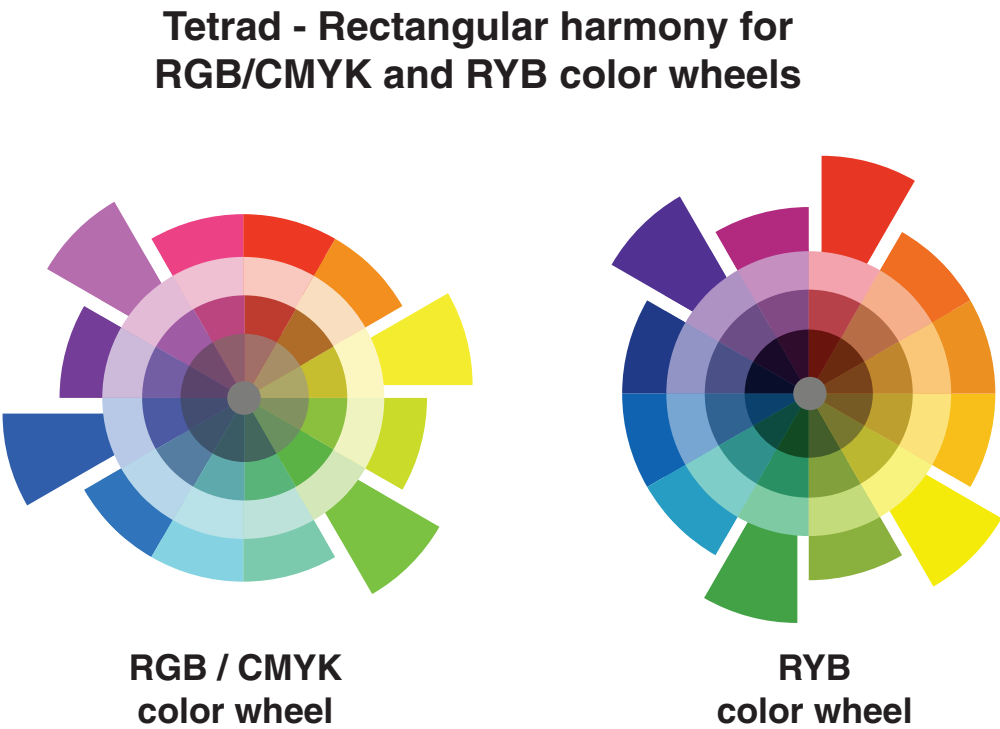


FIGURE 4.22 Tetrad – rectangular color harmony in the key hue of Yellow for the RGB/CMYK and RYB color wheels. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Example of Tetrad - Rectangular harmony

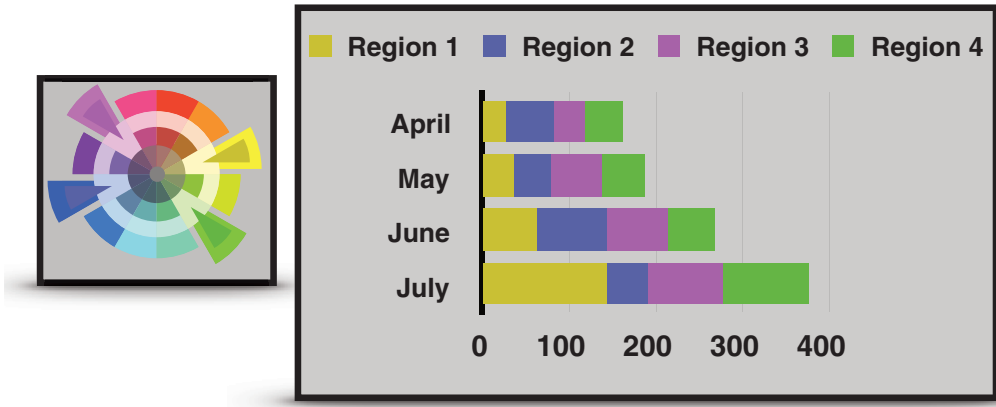


FIGURE 4.23 Example of tetrad – rectangular harmony in the key of Yellow applied to a horizontal two-dimensional stacked bar chart. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

requirement. The two complementary pairs of colors to define the rectangular harmony are Yellow and Blue with Green and Magenta. Using hues and shades of these four colors, we develop a horizontal stacked bar chart. Our results are shown in Figure 4.23.

4.5.7.2 Square Harmony

For a *square* harmony, four colors are equidistant and three steps apart on the color wheel. Together, the four hues form a square on the color wheel that results in two pairs of complements. In Figure 4.24, Yellow and Blue complements combined with Green-Cyan (Aqua Marine) and Magenta-Red (Deep Pink) complements are shown on the RGB/CMYK color wheel along with Yellow and Purple complements combined with Green-Blue and Red-Orange on the RYB color wheel.

4.5.7.2.1 Example of Tetrad – Square Harmony

Here, we build an interactive two-dimensional bar chart of sales data in four regions over a time frame of four months. With each time step (month), the values for each region change. We colorize this interactive information visualization example using a square harmony in the key of Yellow. For this square harmony, all four colors are equidistant and three steps apart on the RGB/CMYK color wheel. The resulting complementary pairs are Yellow and Blue with Green-Cyan and Magenta-Red. Using hues and tints of these four colors, we build the bar elements in this interactive example. Graph lines are added for clarification. Figure 4.25 shows a static image of time step 4 (July) of our results.

4.5.8 Diad Harmony

Diad harmony combines two colors that are two steps apart on the color wheel. Working again with our key hue of Yellow, the Yellow and Red hues are two steps counterclockwise

**Tetrad - Square harmony for
RGB/CMYK and RYB color wheels**

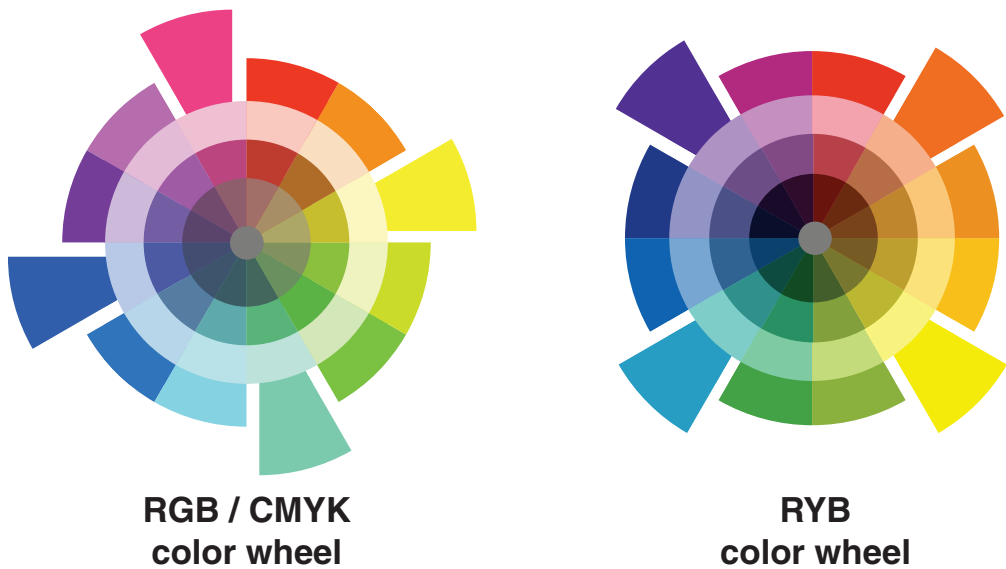


FIGURE 4.24 Tetrad – square color harmony in the key hue of Yellow for the RGB/CMYK and RYB color wheels. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Example of tetrad - Square harmony

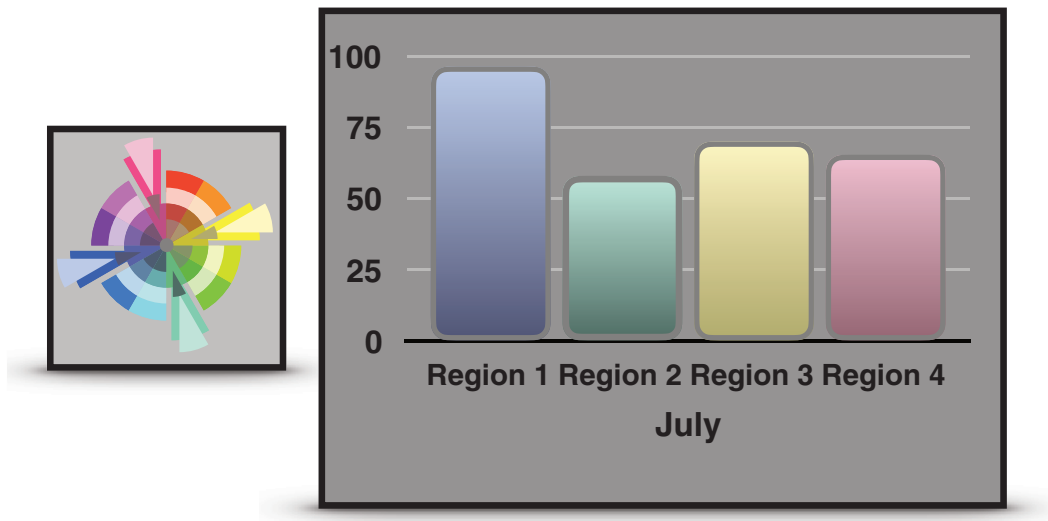


FIGURE 4.25 Example of tetrad – square harmony in the key of Yellow applied to an interactive two-dimensional bar chart. Static image of the last time step is shown here. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Diad harmony for RGB/CMYK and RYB color wheels

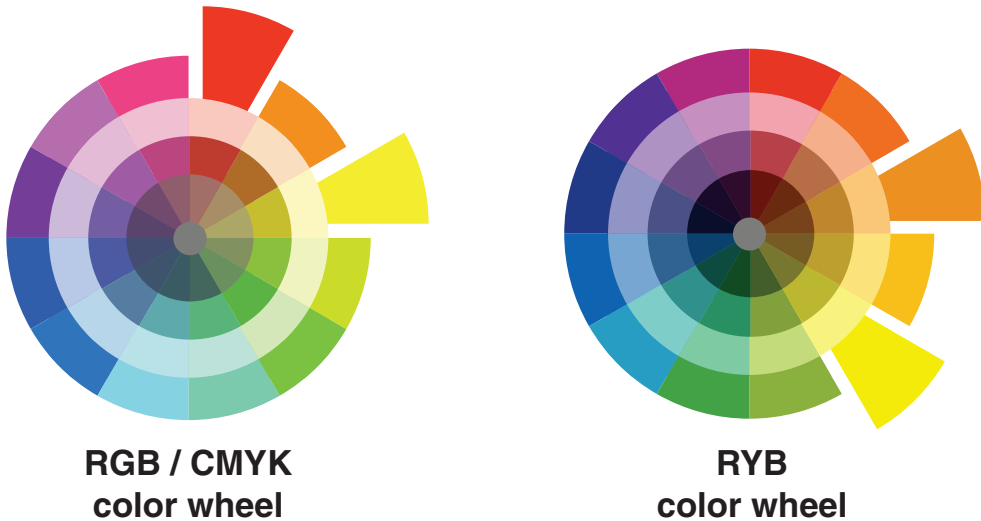


FIGURE 4.26 Diad color harmony in the key hue of Yellow. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

from each other on the RGB/CMYK color wheel. On the RYB color wheel, the Yellow and Orange hues are two steps counterclockwise from each other. Figure 4.26 shows these results for diad harmony.

4.5.8.1 Example of Diad Harmony

In this example, we develop a bubble chart of sales data for a two-month time frame. A diad color harmony is selected to depict the data values. We use Yellow as our key color and move two steps counterclockwise on the RGB/CMYK color wheel to select Red as our second color. Each bubble is highlighted with a Black stroke line. Figure 4.27 depicts our results with Yellow and Red hues and tones applied to our bubble chart data.

4.5.9 Triad Harmony

Triad harmony includes three colors that are equally spaced from each other on the color wheel. The equal spacing creates an equilateral triangle on the wheel. Using the key hue of Yellow, the resulting triad includes the Cyan, Yellow, and Magenta colors on the RGB/CMYK color wheel. This combination encompasses the secondary colors of the RGB color space or the primary colors of the CMYK color space. On the RYB color wheel, the triad for the key hue of Yellow includes the Red, Yellow, and Blue colors. This combination represents the primary colors of the RYB color space. Figure 4.28 shows these results for triad harmony.

Example of diad harmony

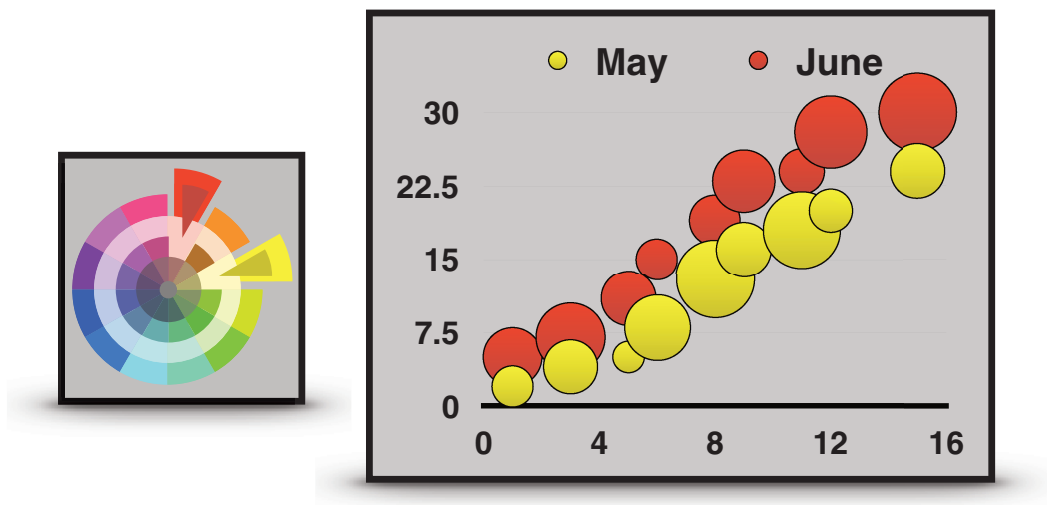


FIGURE 4.27 Example of diad harmony in the key of Yellow applied to a bubble chart data visualization. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Triad harmony for RGB/CMYK and RYB color wheels

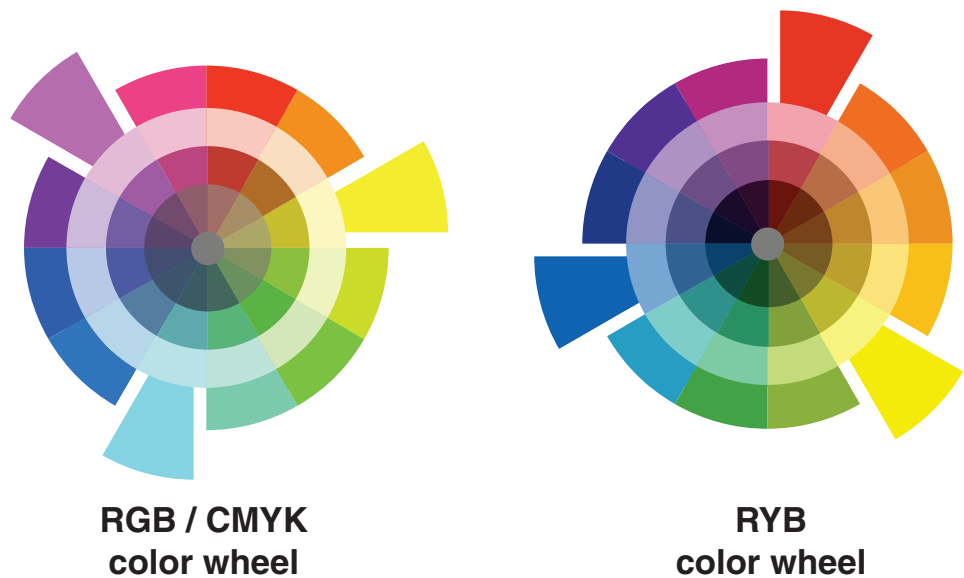


FIGURE 4.28 Triad color harmony in the key hue of Yellow. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

Example of triad harmony

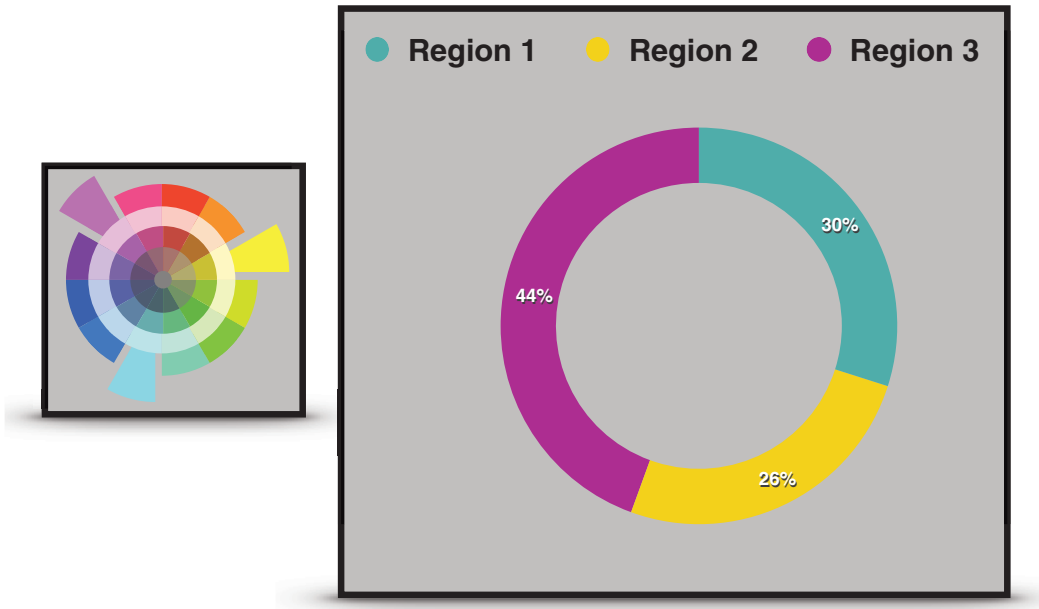


FIGURE 4.29 Example of triad harmony in the key of Yellow applied to a two-dimensional donut chart. Source: image created by Theresa-Marie Rhyne, 2016 & 2024.

4.5.9.1 Example of Triad Harmony

Here, we build a two-dimensional donut chart for percentages of sales data across three regions over one month. A triad color harmony in the key of Yellow is selected to colorize the data associated with the three regions. Our triad harmony includes three colors that are equally spaced from each other on the RGB/CMYK color wheel. With Yellow as the key, the other two colors are Cyan and Magenta. To reduce the vibrancy of the display, we use tones rather than solid hues in this data visualization. This color combination is also both the set of secondary colors for the RGB color model and the set of primary colors for the CMYK color model. Figure 4.29 depicts our results.

4.6 GAMUT MASKING FOR COLOR HARMONY

In the previous section, we presented many types of color harmony. One challenge many designers and painters confront revolves around narrowing down the color wheel possibilities to only focus on a specific group of colors when creating or building the color content. *Gamut masking* is an approach for defining a specific range of colors or a color harmony grouping on the color wheel. In 2010, James Gurney, a highly regarded author and illustrator of the *Dinotopia* series, outlined his approach to what he called “Color Wheel or Gamut Masking” in his book on *Color and Light: A Guide for the Realist Painter* [7]. Gurney showed how one could cut out, or mask, only portions of the color wheel that were desired

for a given color scheme. This allowed for focusing on a subset of the color wheel in developing the color palette for a given painting. Richard Robinson built an online tool entitled “Gamut Masking” inspired from Gurney’s writings [8,9]. Robinson’s tool provides either the RYB color wheel for painters or the RGB/CMYK color wheel for photographers, printers, and digital content developers to facilitate the color wheel masking process. Robinson defines the RYB color wheel as the “Standard” wheel and the RGB/CMYK color wheel as the “Yurmby” (Yellow, Red, Magenta, Blue, Cyan, Green) color wheel. Each color wheel also spins colors around for more interactive exploration of color harmony. Robinson’s tool, endorsed by James Gurney, is available under Robinson’s “My Painting Club” website at <https://mypaintingclub.com/blog/post/39-The-Gamut-Mask-Tool>.

A laptop or desktop computing environment produces the best results when running the Gamut Mask Tool.

In Figure 4.30, we use the Color Gamut Mask Tool with the Yurmby (RGB/CMYK) color wheel option to develop a three-dimensional stacked area chart. The sample data set of sales over a four-month period used in Section 4.5 of this chapter is used to generate the numeric values for the infographic or information visualization. We apply the cool color concept noted in Section 4.4 of this chapter and develop a mask for the analogous colors of Green-Cyan, Cyan, and Cyan-Blue. Our color gamut mask also provides us with a sense of how color quantities will appear when we apply the analogous colors of Green-Cyan, Cyan, and Cyan-Blue to our stacked area chart.

Using the color gamut mask tool for an infographic design

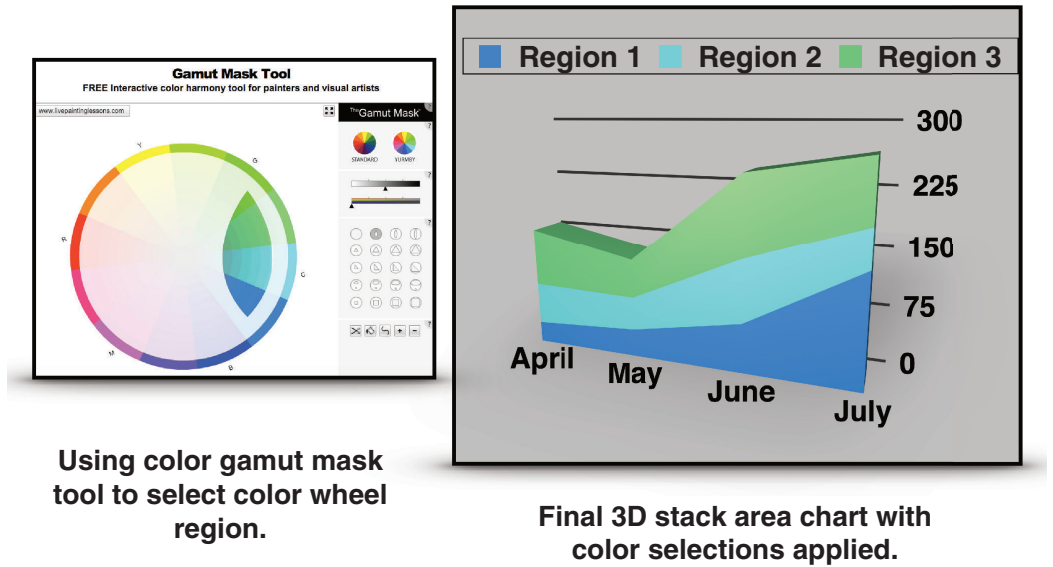


FIGURE 4.30 Using the Color Gamut Mask Tool for an infographic design. Source: image created by Theresa-Marie Rhyne, 2016 & 2024, using the Color Gamut Mask Tool, <https://mypaintingclub.com/blog/post/39-The-Gamut-Mask-Tool>.

4.7 REVISITING THE HISTORICAL EVOLUTION OF THE COLOR WHEEL AND COLOR HARMONY

Now that we have discussed the construction of color wheels and defined color harmony, we can revisit the historical evolution of the color wheel. There were and are many contributors to color theory over the centuries in the Western World. We highlight a select few who helped define concepts pertaining to the evolution of the color wheel and color harmony. For a more robust discussion of the history of color theory in the Western World, we refer you to Rolf G. Kuehni and Andreas Schwarz's 2008 book on *Color Ordered: A Survey of Color Order Systems from Antiquity to the Present* [10]. In the References section, we also list original source materials as further readings about the contributions to color harmony we will describe here.

4.7.1 Revisiting Isaac Newton's Color Circle

As we noted in Chapter 1, Isaac Newton developed the initial concept of the color circle or the color wheel and published it in his 1704 book, entitled *Opticks* [11]. Newton's color wheel was based on depicting colors in the spectrum of light in a closed circle. Figure 1.10 shows Newton's color circle diagram. Newton's diagram was fundamental in its geometry but did not include color relationships as a concept.

4.7.2 Revisiting Moses Harris's Color Wheels

In 1766, over 60 years after Isaac Newton's writings on the color circle, Moses Harris further evolved the color wheel in his *Natural System of Colours* book [12]. Harris made the first known published attempt to diagram the RYB color wheel. He defined a "prismatic" or primary color wheel for RYB, as well as a "compound" color wheel for the secondary colors of Orange, Green, and Purple. The Harris's color wheels are shown in Figure 1.11 and included 18 divisions on the wheel. Following similar steps to what we defined in Section 4.2.3 of this chapter, Harris included the primary RYB colors, the secondary RYB colors of Orange, Green, and Purple, and the tertiary colors that mix a primary and secondary color on his prismatic color wheel. Harris chose a finer level of detail for the tertiary colors. Harris noted, for example, that Orange-Red was a different color from Red-Orange as we move clockwise from Red at the top of his color wheel. He did not specifically develop complementary color relationships. Harris's work functioned as an inventory of hues, tones, and shades of colors similar to concepts we noted in Section 4.3 of this chapter.

4.7.3 Revisiting Johann Wolfgang von Goethe's Color Wheel

In his 1810 *Theory of Colours* publication, Johann Wolfgang von Goethe defined the color wheel in a format similar to what we are familiar with today [13]. Goethe developed a symmetric color wheel composed of colors that oppose or complement each other where complementary colors cancel each other out to produce Gray or Black when mixed as pigments. Figure 1.12 shows Goethe's concept that is similar to our discussions on the first two steps in constructing a color wheel in Section 4.2 of this chapter. As we noted in Section 1.5 of Chapter 1, another significant contribution that Goethe made was to include Magenta

as a color in his color theories. As we noted in Figure 2.10 in Chapter 2, Magenta is not a spectral color. However, it is a color we, as humans, mentally see in afterimages produced by our brain. Magenta is also a primary color of the printing process. Goethe's addition of Magenta or Red-Purple also provided an effective closure to the color wheel between Purple and Red and thus has remained on color wheels to this day.

4.7.4 Examining Phillipp Otto Runge's Color Sphere

Phillipp Otto Runge, a contemporary of Goethe, developed and published one of the first recognized three-dimensional sphere models in color theory. Runge defined the complete space of color as consisting of the RYB chromatic primaries, Black and White achromatic primaries, and their mixtures. He built a color circle with RYB forming the primaries, as well as Orange, Green, and Purple forming the secondary colors on the color wheel as we show in Figure 4.3. He conceived of a color sphere with White forming the top and Black forming the bottom opposing poles of the sphere. Runge published his color sphere concept in a manuscript entitled *Die Farbenkugel* (The Color Sphere) in 1810 and unfortunately died shortly thereafter [14,15]. Goethe later published key letters from Runge in Goethe's own publications. Runge used the color sphere to define pleasing or discordant color combinations, thus developing color harmony concepts. Many contributors to color theory built upon Runge's work. These individuals include Albert Munsell and Johannes Itten. As we noted in Section 3.8 of Chapter 3, Albert Munsell revitalized the color sphere concept in Munsell's early efforts to develop a color notation system. However, Munsell soon discovered that a perceptual uniform color space was not naturally geometrically regular. Munsell abandoned the color sphere concept to build his color system on equally perceived color differences that produced branching geometry called a color tree, shown as Figure 3.10 of Chapter 3. Later in this section, we will discuss the contributions of Johannes Itten and his colleagues at the Bauhaus in the 1920s to color harmony and art education. In Figure 4.31, we show Runge's initial color sphere concept that he hand-drew for his 1810 "The Color Sphere" publication [16].

4.7.5 Revisiting Michel Chevreul's Color Wheel

As noted in Chapter 1, Michel Chevreul further emphasized complementary colors on the color wheel to support his color contrast concepts that appeared in his 1839 book on *The Principles of Harmony and Contrast of Colours, and Their Application to the Arts* [17]. Figure 1.14 depicts the color wheel Chevreul developed. Chevreul's actually defined a hemispherical color model to predict his contrast effects where the color wheel is the bottom cross section of the hemisphere. Following similar steps to what we noted in Section 4.2.3 of this chapter, Chevreul located the RYB primaries and the Orange, Green, and Purple secondary colors at equal sixths around the circumference of his color wheel. The tertiary colors were added between the primary and secondary colors. Chevreul added finer divisions to his color wheel by dividing each twelfth into six intervals for a wheel of 72 hues. Chevreul also specifically insured that a hue and its direct complement opposed each other on his color wheel to emphasize his color harmony and contrast concepts.

Runge's color sphere illustration, created in 1810

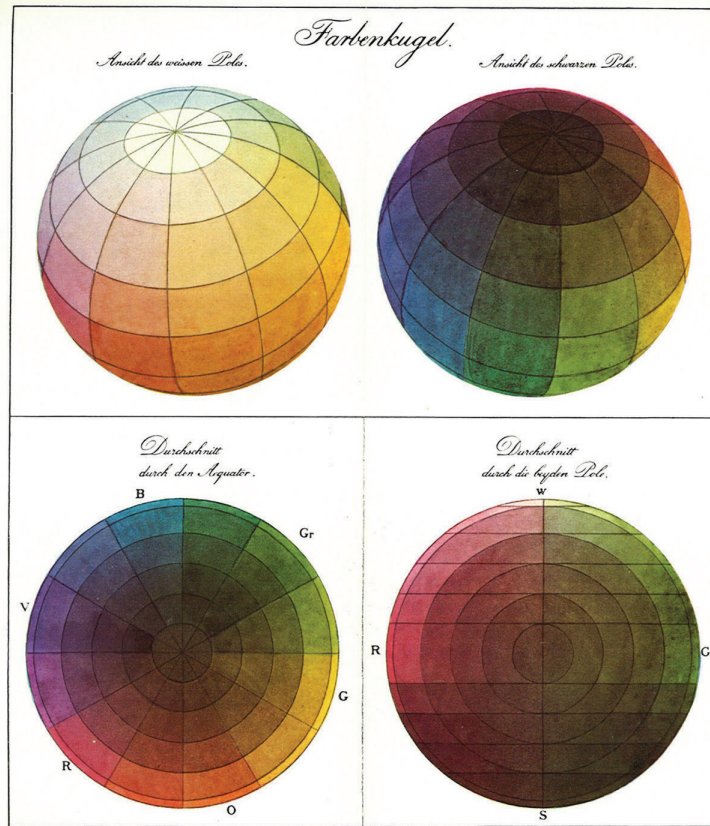


FIGURE 4.31 Phillipp Otto Runge's color sphere hand-painted illustration. From References [15,16]. Public domain.

4.7.6 Exploring George Field's Color Wheel

In a similar time frame, George Field, trained as a chemist, manufactured and sold paint colors for artists in Great Britain. Field experimented with various production methods of color pigments, and his products were well regarded among professional artists. In 1817, he published *Chromatics, Or, an Essay on the Analogy and Harmony of Colours* that outlined color harmony concepts for the RYB color model [18]. His 1835 publication on the *Chromatography, or, a Treatise on Colours and Pigments, and of Their Powers in Painting* presented practical concepts about color that encompassed pigments, as well as drying and preserving products [19,20]. His second book became a key reference on color for painters and other artists. From his extensive testing efforts, Field offered detailed observations of close to all of the commercially available pigments at the time of publication of his writing. He thus provided a reliable handbook and the framework for revisions to the book that aided artists for years to come. Field provided detailed discussions of tertiary colors, the combinations of primary and secondary colors, and developed a detailed color wheel

Field's color wheel illustration, created in 1835

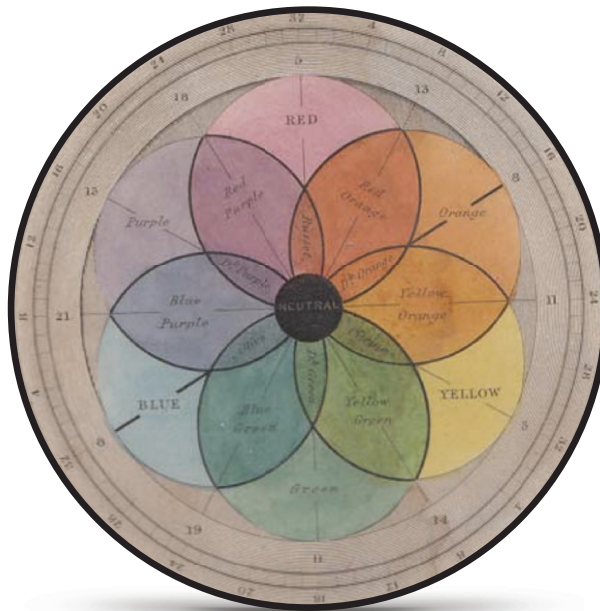


FIGURE 4.32 George Field's color wheel illustration. From Reference [19]. Public domain.

of pigment mixtures. Field's terminology and diagram are still widely regarded today in terms of RYB color pigment mixing and color harmony. Field also included a chapter on "new optical instruments" with light and color experiments noted. Many of Field's notions on light and color from the RYB color model perspective, however, were proven to be in error with James Clerk Maxwell's 1861 demonstration of the RGB color model that we highlighted in Section 1.1 [21] of Chapter 1. In Figure 4.32, we show George Field's color wheel from his *Chromatography, or, a Treatise on Colours and Pigments, and of Their Powers in Painting* book. The hand-painted Red and Blue hues have faded with time, but the labeling still remains.

4.7.7 Examining Ogden N. Rood's *Modern Chromatics* Writings

In 1879, Ogden N. Rood published his book on *Modern Chromatics, with Applications to Art and Industry*. The book was also translated into German in 1880 and French in 1881. Rood was a professor of Physics at Columbia University and an amateur painter. His book presented trichromatic color vision concepts with a focus on Thomas Young's work, defined color harmony, discussed color contrasts, and addressed mixing of pigment paints in detail. He presented many of the color concepts that Newton, Goethe, Chevreul, Field, and others had developed in a format that was understandable to a "lay person" and appealed to artists. Rood also developed an early hue, saturation, and brightness model similar to the hue, saturation, and value concepts we have presented in Section 3.9 of Chapter 3 of this book. In an appendix, the *Modern Chromatics* book also mentioned Hering's opponent

Front plate of rood's modern chromatics book: published in 1879

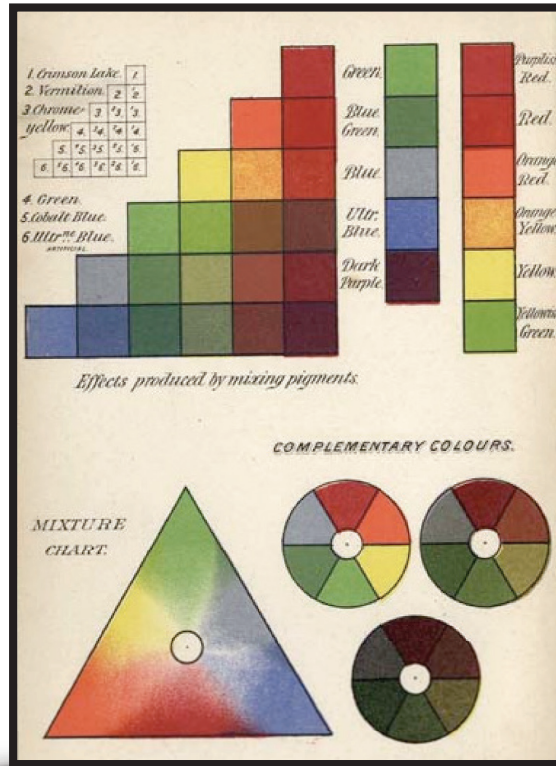


FIGURE 4.33 Front plate illustration from Ogden N. Rood's *Modern Chromatics* book. From Reference [22]. Public domain.

color theory notions. Rood's book was credited as being hugely influential to Impressionist and Neo-Impressionist artists of the time. George Seurat's pointillism painting style was influenced by readings of Rood's discussion on the theory of contrasting colors [23]. We show illustrations from Rood's *Modern Chromatics* book in Figure 4.33.

4.7.8 Examining Color Wheel Instruction Writings by Louis Prang and Milton Bradley Although Rood described the RGB color model and the resulting RGB color wheel in a format artists could understand, many practicing artists and art educators continued to use the RYB color model when it came to discussing color pigments and color harmony. In 1893, Louis Prang, Mary Dana Hicks, and John S. Clark published the book, *Instruction in Color for Public Schools*, and defined a color wheel similar to the RYB color wheel we show in Figure 4.3 of this chapter [24]. This color wheel is frequently called the Prang color wheel after Louis Prang who described it and color harmony concepts for art education purposes. Interestingly, Louis Prang is also known as the “father” of the American Christmas

card. In the 1890s, Milton Bradley, the founder of the Milton Bradley Company known for creating board games, published several books on color instruction at the primary and secondary school levels. His book on *Elementary Color* provided guidelines for teaching color pigment mixing and color harmony with the RYB color model [25]. As a result of these and other contributions, the RYB color wheel and color harmony concepts became fundamental to kindergarten and elementary school education.

4.7.9 Exploring Bauhaus Contributions to Color Harmony and Interaction

From 1919 to 1933, an art school in Germany operated that combined a unique approach to design with crafts and fine arts. The Bauhaus school was founded on the basis of creating a “total” work of art in which all arts could be brought together. This concept encompassed textiles, painting, sculpture, graphics design, interior design, architecture, industrial design, and typography, as well as other design disciplines. Color theory was a basic part of the curriculum and included in the first-year preliminary course among others. Several Bauhaus instructors rotated teaching the preliminary course, as well as expressing their notions of color theory in other classes. We review key concepts introduced by four Bauhaus instructors who highlighted color: Paul Klee, Wassily Kandinsky, Johannes Itten, and Josef Albers. Each of these instructors interacted with each other while at the Bauhaus, and it is possible to observe some blending of their concepts. Each artist, however, maintained their own unique approach to presenting color fundamentals via the RYB color model and wheel in their teachings and individual art compositions.

4.7.9.1 Paul Klee’s Teachings of Color

Paul Klee discussed differences between the visual perception of color pigments and the nature of color as a light. Klee also highlighted how colors are altered with changes in the purity or intensity of a color (saturation), as well as changes in the lightness or darkness of a color (value). We featured some of these changes previously in Figure 4.4. In his teachings of color, Klee highlighted the relationship between hue, chroma (also termed colorfulness), and value using the color wheel that was at the equator of a color sphere similar to Philip Otto Runge’s sphere noted in Figure 4.31. Klee produced detailed notebooks on his lectures that are available today in a multimedia format as the *Notebooks of Paul Klee, Volume 1 & 2*. We list these writings in the References section at the end of this chapter [26,27].

4.7.9.2 Wassily Kandinsky’s Teachings of Color

Wassily Kandinsky taught Bauhaus students about the notion that color itself, not necessarily the object colored, evokes a perceptual response. As a result, the juxtaposition of line and color can result in a sense of movement. Figures 4.21 and 4.27 are two examples of implementations of this concept. Prior to his arrival at the Bauhaus in 1922, Kandinsky released a significant treatise entitled “*On the Spiritual in Art*” in 1910 that was translated from German into English in 1911 [5]. In this essay, Kandinsky advanced the concepts of abstract art by expressing his belief that color could be used in a painting independently of the visual description of an object or scene. At the Bauhaus, Kandinsky taught the preliminary course where he further evolved color concepts beyond the warm and cool concepts we noted in Section 4.4 of this chapter.

4.7.9.3 Johannes Itten's Teachings of Color

Johannes Itten pioneered the teaching of the preliminary course at the Bauhaus in 1919. Itten used the RYB 12-sectioned color wheel of primary, secondary, and tertiary colors similar to what we have diagrammed in Figure 4.5. His teachings highlighted color harmony and color contrasts. Like Klee and as previously noted, Itten also defined a color sphere concept that extended the concepts of Phillip Otto Runge. A two-dimensional cross section of Itten's color sphere, based on the RYB color model, is frequently called a "Color Star". Many of his color theory concepts appeared in a book he later (1961) published in German entitled *The Art of Color: The Subjective Experience and Objective Rationale of Color*. After Itten's death in 1967, Faber Birren published a condensed and simplified version of Itten's original writings and entitled it *The Elements of Color: A Treatise on the Color System of Johannes Itten Based on His Book 'The Art of Color'*. Birren's condensed version was officially published in 1970. These references are cited in the References section of this chapter. Itten's discussions of the RYB color model and color harmony concepts are still used to introduce students to color today [28,29].

4.7.9.4 Josef Albers's Teachings of Color

Josef Albers's teachings focused on the concept that the perception of color is always relative and subjective. Albers developed student exercises that demonstrated how color deceives continually. In Figure 4.19, Albers's concepts are illustrated where the addition of a solid White circle inside the Cyan, Blue, and Purple data points creates a three-dimensional vibrating affect. In Figure 4.21, although a two-dimensional bar chart is shown, the Yellow, Orange, Blue, and Cyan-Blue rectangles when combined create a three-dimensional perception. Albers's teachings and exercises emphasized that applying rules of color harmony does not always address color interactions and deceptions. Josef Albers originally came to the Bauhaus as a student from 1920 to 1923, enrolling in the preliminary course taught by Itten and attending glass painting workshops. In 1923, he was appointed to the teaching staff and given a commission to teach the preliminary course. From 1925 until the Bauhaus closure in 1933, Albers served as either the co-director or the director of the preliminary course. During this time frame, Albers began to develop many of his notions about color being the primary medium of pictorial language. Albers met and married Anni Albers, who went on to pioneer in textile arts, during the Bauhaus years [32]. After the closure of the Bauhaus, the husband and wife team immigrated to the USA and taught at Black Mountain College in Asheville, North Carolina. The couple left Black Mountain and eventually moved on to Yale University in 1950, where Josef Albers lead and taught in the Department of Design until his retirement in 1958. They remained at Yale University until their respective deaths. Many of Josef Albers's students, such as Kenneth Nolan, pioneered abstract painting movements like *Color Field Painting* [30–32].

From 1949 until his death in 1976, Josef Albers explored colors and chromatic interactions with nested squares in his paintings and prints entitled collectively "*Homage to a Square*". In 1963, he published the book, *Interaction of Color* [6]. The book was conceived as a handbook and teaching aid to explain complex color theory principles to artists, instructors, and students. The original version, published by Yale University Press, was a limited silkscreen edition with 150 color plates. In 1971, a paperback version that featured ten color

studies chosen by Albers was released and continues to remain in print. Albers’s landmark book includes case studies and exercises on: (1) color relativity, intensity, and temperature; (2) color contrasts such as vibrating and vanishing boundaries; and (3) optical illusions of transparency and reversed grounds. His intent was not to develop a set of color harmony rules or guidelines. Rather, Albers designed his book to be a set of opportunities to discover and explore the magic of color. The *Interaction of Color* is considered to be one of the most comprehensive examinations of the function and perception of color to this day. The book profoundly influenced art education and art practice in the twentieth century and continues to do so today. Reference [6] provides a specific citation of the 50th anniversary edition of the book.

4.8 MODERNIZING ALBERS’S INTERACTION OF COLOR STUDIES WITH A WEBSITE

In 2023, Yale University Press released the *Interaction of Color Complete Digital Edition* website, <https://interactionofcolor.com> [33]. Individual users can purchase access to the website and all its content for \$24.99. This allows for viewing the full text of the book, all the plates, and supplemental video content. The website is a near-digital replica of the 1963 version of *the Interaction of Color* book including the implementation of the original Baskerville typeface and layout of the text columns with 21st-century upgrades. These upgrades include videos on the usage of color in practice. There are also historic videos, from the Josef and Anni Albers Foundation, where Josef Albers describes his purpose for creating the book [34]. Additionally, you can experiment with recoloring the plates to create your own versions of the original color illustrations. Your studies can be saved in your specified *Workspace* and later exported to your own computer. In Figure 4.34, we work with *Plate XVIII-2b Free Studies – a challenge to the imagination*. We have recolored a blank version of the original plate to achieve a very different result.

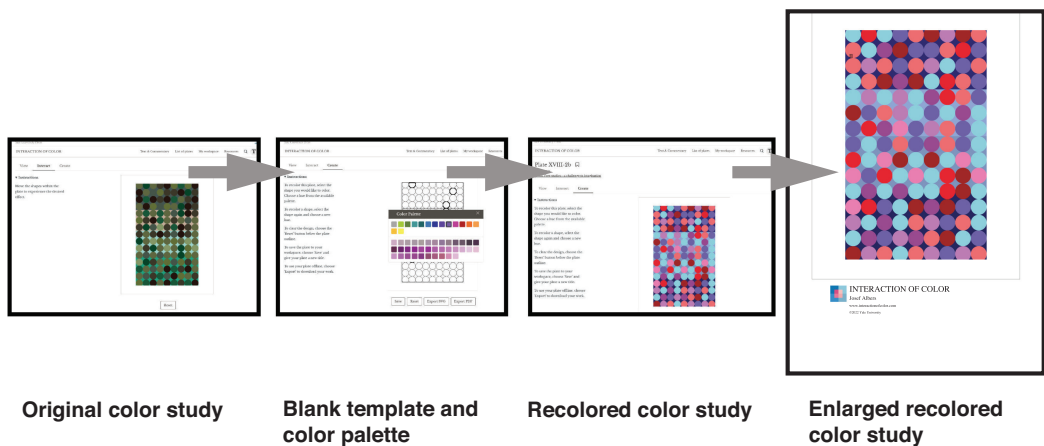


FIGURE 4.34 Recoloring **Plate XVIII-2b Free Studies – a challenge to the imagination** using the templates in the *Interaction of Color Complete Digital Edition* website <https://interactionofcolor.com>. Source: image created by Theresa-Marie Rhyne, 2024 using the “Interaction of Color” website templates. Shown with granted permission from Yale University Press.

4.9 CONCLUDING REMARKS

In this chapter, we reviewed the color wheel for the respective RGB, CMYK, and RYB color models. We showed hues, tints, tones, and shades on the color wheel. Next, we defined color harmony as the process of choosing colors, from the color wheel, that work well together in the composition of an image. Nine types of color harmony with an example for each were presented: (1) monochromatic; (2) analogous; (3) complementary; (4) split complementary; (5) analogous complementary; (6) double complementary; (7) tetrad – rectangular and square; (8) diad; and (9) triad. We also revisited the historical evolution of the color wheel and color harmony building on our preliminary review in Section 1.5 of Chapter 1. In Chapter 5, we will introduce the concept of data color schemes and how they relate to the color harmony concepts presented here.

REFERENCES

1. Eldridge, K. (2008), *The Complete Color Harmony Workbook*, Gloucester, MA: Rockport Publishers.
2. Smith, K. (2024), “Sensational Color”, <https://www.sensationalcolor.com/>, accessed March 1, 2024.
3. Canva (2024), “Color Wheel”, <https://www.canva.com/colors/color-wheel/>, accessed March 1, 2024.
4. Briggs, D. (2013, “Part 7. The Dimension of Hue”, *The Dimensions of Color*, <http://www.huevaluechroma.com>, accessed August 24, 2024.
5. Kandinsky, W. and Sadler, M.T.H. (2008), *Concerning the Spiritual in Art*, Auckland, NZ: The Floating Press (first published in 1911), https://books.google.com/books?id=03ugtxqGZYMC&printsec=frontcover&source=gbg_summary_r&cad=0#v=onepage&q&f=false, accessed March 3, 2024.
6. Albers, J. (2013), *Interaction of Color: 50th Anniversary Edition*, New Haven, CT: Yale University Press.
7. Gurney, J. (2010), *Color and Light: A Guide for the Realist Painter*, Kansas City, MO: Andrews McMeel Publishing.
8. Gurney, J. (2011), “Part3. Gamut Masking Method”, *Gurney Journey*, <https://gurneyjourney.blogspot.com/2011/09/part-3-gamut-masking-method.html>, accessed March 3, 2024.
9. Robinson, R. (2010), “Gamut Mask Tool”, *My Painting Club*, <https://mypaintingclub.com/blog/post/39-The-Gamut-Mask-Tool>, accessed March 3, 2024.
10. Kuehni, R.G. and Schwarz, A. (2008), *Color Space and Its Divisions: Color Order from Antiquity to the Present*, New York: Oxford University Press.
11. Newton, I. (1704), *Opticks: or, a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light. Also, Two Treatises of the Species and Magnituder of Curvilinear Figures*, London: Samuel Smith and Benjamin Walford. Available from The Project Gutenberg EBook of Opticks: <https://www.gutenberg.org/files/33504/33504-h/33504-h.htm>, accessed March 08, 2024.
12. Harris, M. (1766), *The Natural System of Colors*, Leicester–Fields: Laidler.
13. von Goethe, J.W. (1840), *Goethe’s Theory of Colours*, Translated with notes by RAFRS Charles Lock Eastlake. London: John Murray, <https://archive.org/details/goethestheoryco01goetgoog>, accessed March 03, 2024.
14. Kuehni, R.G. (2008), “Philipp Otto Runge’s Color Sphere: A Translation with Related Materials and an Essay”, <https://www.web3.lu/download/RungeFarben-Kugel.pdf>, accessed March 03, 2024.
15. Runge, P.O. (1810), *Die Farben-Kugel (Color Sphere), oder Construction des Verhaeltnisses aller Farben zueinander*, Hamburg: Perthes.

16. Stahl, G. (2010) (trans), *On Vision and Colors by Arthur Schopenhauer and Color Sphere by Phillip Otto Runge*, Translated by G Stahl. New York: Princeton Architectural Press.
17. Chevreul, M.E. (1839), *De la loi du contraste simultané des couleurs et de l'assortiment des objets colorés*, Paris, English transl. by Charles Martel as *The Principles of Harmony and Contrast of Colours*. London: Longman, Brown, Green and Longmans.
18. Field, G. (1817), *Chromatics: An Essay on the Analogy and Harmony of Colours*, London: A.J. Valpy, Tookes Court, Chancery Lane.
19. Field, G. (1835), *Chromatography: Or, a Treatise on Colours and Pigments, and of Their Powers in Painting*, London: Charles Tilt, Fleet Street.
20. Shires, L.M. (2016), "On color theory, 1835: George Field's chromatography," *BRANCH: Britain, Representation and Nineteenth-Century History*, DF Felluga, eds., Extension of Romanticism and Victorianism on the Net, https://www.branchcollective.org/?ps_articles=linda-m-shires-on-color-theory-1835-george-fields-chromatography, accessed March 03, 2024.
21. British Journal of Photography (1861), "The Theory of the Primary Colors", https://web.archive.org/web/20130612071037/https://notesonphotographs.org/index.php?title=%22The_Theory_of_the_Primary_Colours.%22_The_British_Journal_of_Photography,_August_9,_1861, accessed March 03, 2024.
22. Rood, O.N. (1879), *Modern Chromatics, with Applications to Art and Industry*, New York: D. Appleton and Company.
23. Russell, J. (1965), *Seurat*, London, UK: Thames and Hudson.
24. Prang, L., Hicks, M.D., and Clark, J.S. (1893), *Suggestions for a Course of Instruction in Color for Public Schools*, New York: The Prang Educational Company.
25. Bradley, M. (1895), *Elementary Color*, 3rd ed., Springfield, MA: Milton Bradley Company.
26. Klee, P. and Spiller, J. (2014), *The Notebooks of Paul Klee, Volume 1 the Thinking Eye*, San Francisco, CA: Wittenborn Art Books (Multimedia CD).
27. Klee, P. and Spiller, J. (2014), *The Notebooks of Paul Klee, Volume 2 the Nature of Nature*, San Francisco, CA: Wittenborn Art Books (Multimedia CD).
28. Itten, J. (1974), *The Art of Color: The Subjective Experience and Objective Rationale of Color*, Hoboken, NJ: John Wiley & Sons.
29. Itten, J. and Birren, F. (1970), *The Elements of Color: A Treatise on the Color System of Johannes Itten Based on His Book "The Art of Color"*, Hoboken, NJ: John Wiley & Sons.
30. The Art Story (2016), "Color Field Painting", <https://www.theartstory.org/movement-color-field-painting.htm>, accessed March 03, 2024.
31. The Art Story (2016), "Kenneth Noland", <https://www.theartstory.org/artist-noland-kenneth.htm>, accessed March 3, 2024.
32. Weber, N.F. (2020), *Anni and Josef Albers: Equal and Unequal*, New York: Phaidon Press, <https://albersdesignshop.bigcartel.com/product/anni-josef-albers-equal-and-unequal>, accessed March 11, 2024.
33. Yale University Press (2023), *Interaction of Color Complete Digital Edition*, <https://interactionofcolor.com>, accessed March 11, 2024.
34. The Josef & Anni Albers Foundation (2024), "The Alberses' Ideas Remain Alive and Will Do So into the Future", <https://www.albersfoundation.org/alberses>, accessed March 11, 2024.

Translating Between Color Harmony and Data Color Schemes

IN CHAPTER 4, WE defined the fundamentals of color harmony based on the color model and the color wheel you are using. We also showed how these concepts evolved and were defined by color artists and scientists over many centuries. In the field of data visualization, there is a different approach to building color schemes based on the kind of data you are examining. These *data color schemes* are divided into three types of classifications: sequential, diverging, and qualitative. In this chapter, we discuss these three classifications of data color schemes and how they relate to color harmony fundamentals.

5.1 HISTORICAL EVOLUTION OF DATA COLOR SCHEMES

The concept of data color schemes was conceptualized by Cynthia Brewer, a professor of geography and color expert at Pennsylvania State University. In 1994, she diagrammed her classification of data color schemes in “Color Use Guidelines for Mapping and Visualization”, Chapter 7 of *Visualization in Modern Cartography* [1]. From 2001 to 2002, with funding from the US National Science Foundation’s Digital Government Program, she and her student, Mark Harrower, developed the online tool, “ColorBrewer: Color Advice for Cartography” [2]. In 2009, an upgraded version, ColorBrewer Version 2.0 (<https://colorbrewer2.org/>), was released by Axis Maps that is freely accessible [3,4]. The ColorBrewer tool uses the Munsell color model that we discussed in Section 3.8 of Chapter 3. It is also considered to address perceptual uniformity that was noted in Section 3.10 of Chapter 3. Data color schemes have become a fundamental building block in producing data visualizations as described in Chapter 10 of the *Visualization Analysis and Design* textbook by Tamara Munzner [5].

Types of data color schemes in ColorBrewer 2.0

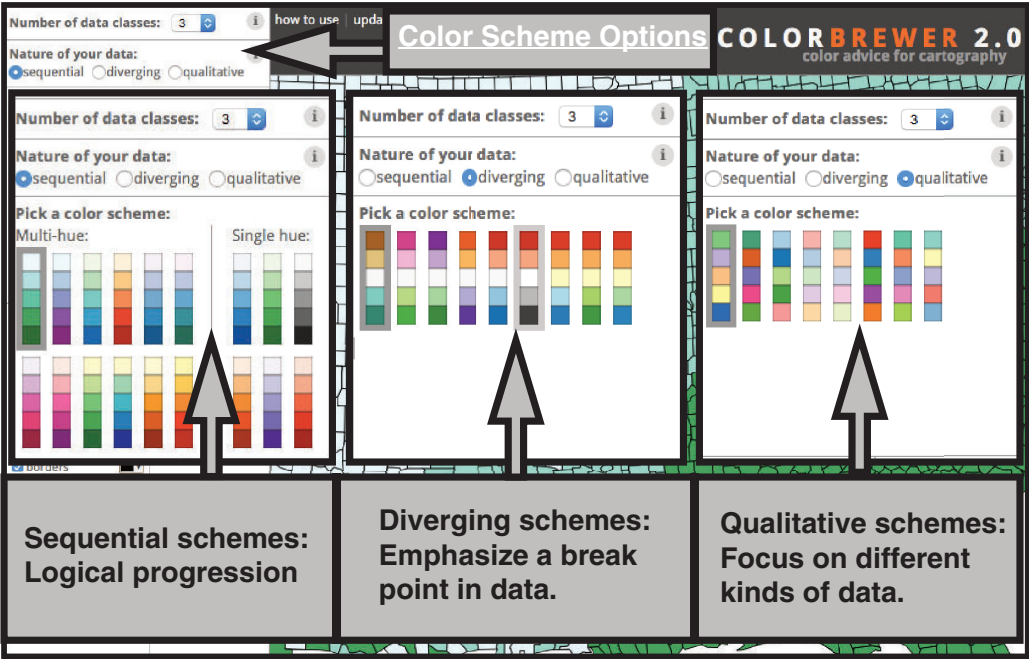


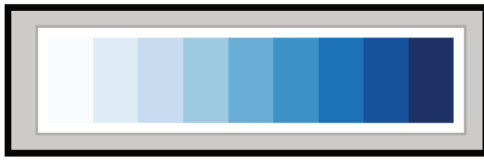
FIGURE 5.1 Three classifications or types of data color schemes using the ColorBrewer 2.0 Web app. Image created by Theresa-Marie Rhyne, 2016 & 2024, with elements from the ColorBrewer 2.0 tool, <http://colorbrewer2.org>.

5.2 THE THREE TYPES OF DATA COLOR SCHEMES

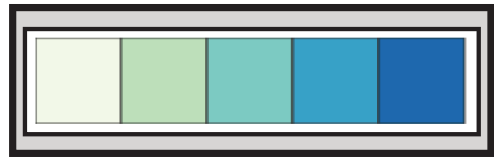
As noted earlier, there are three classifications of data color schemes: *sequential*, *diverging*, and *qualitative*. Sequential schemes are designed for ordering numeric information where colors progress from low to high (or vice versa). Diverging schemes emphasize quantitative data that progresses outward from a central neutral midpoint to two different color extremes. Qualitative schemes are designed for coding categorical information when there is no particular ordering of the data and colors should receive equal perceptual weight. In Figure 5.1, we show the three classifications of data color schemes using the ColorBrewer 2.0 Web app.

5.3 THE SEQUENTIAL COLOR SCHEME

Sequential color schemes are optimized for ordered data such as temperature, elevation, income, or infection rates. The standard convention is for the sequence to progress from a light color, representing low attribute values, to a dark color, representing high attribute values. These sequences are composed of either a single-hued or multi-hued progression. In Figure 5.2, we show examples of a Blue (single-hue) sequential color scheme and a Green-Blue (multi-hue) sequential color scheme.



Blue (single-hue) sequential color scheme using ColorBrewer



Green Blue (multi-hue) sequential color scheme using ColorBrewer

FIGURE 5.2 Examples of a Blue (single-hue) sequential color scheme and a Green-Blue (multi-hue) sequential color scheme. Image created by Theresa-Marie Rhyne, 2024, with elements from the ColorBrewer 2.0 tool, <http://colorbrewer2.org>.

5.3.1 Single-Hue Sequential Sequences and Monochromatic Color Harmonies

As we noted in Section 4.5.1 of Chapter 4, a *monochromatic* color harmony combines one hue (a 100% saturated color) with various tints, tones, and shades of that hue to create a color scheme. On the color wheel, the colors of a monochromatic harmony form a straight line from the center of the wheel to the location of the solid hue. This harmony pairs well with the concept of a *single-hue sequential* sequence that progresses from light to dark.

In Figure 5.3, we show a comparison of a Blue monochromatic harmony with a Blue sequential scheme. The Blue monochromatic color harmony was created with the Adobe Color (<https://color.adobe.com/>) suggestion tool, while the Blue sequential scheme was created with ColorBrewer. Chapter 6 will highlight, in further detail, how to use and work with these color suggestion tools [4,6].

5.3.2 Multi-hue Sequential Sequences and Analogous Color Harmonies

As discussed in Section 4.5.2 of Chapter 4, an *analogous* color harmony refers to selecting colors that are next to each other on the color wheel. Multi-hue sequential color schemes are sequences of colors that progress from light to dark and are also adjacent to each other on the color wheel. Figure 5.4 shows a comparison of a typical Cyan Analogous color harmony, built with the aid of the Adobe Color app, and a Green-Blue color sequence, extracted from ColorBrewer. The color wheel from Adobe Color is used as a plotting tool to verify that each color scheme contains elements adjacent to each other on the wheel. The similarities are remarkable. A multi-hue sequential color scheme is a special case of the application of the analogous color harmony where each color is ordered in a systematic progression.

5.4 THE DIVERGING COLOR SCHEME

Diverging color schemes place equal emphasis on both a specified mid-range value and two extreme critical values. They are created by joining two sequential color sequences together with a neutral midpoint. The data color scheme is often used for data that include a critical midpoint value (the mean, median, or zero value) and a data distribution with two ends of importance. Depicting temperature data values that are either cold or hot with a neutral midpoint, elevation data that is either above or below sea level, or voter responses that are

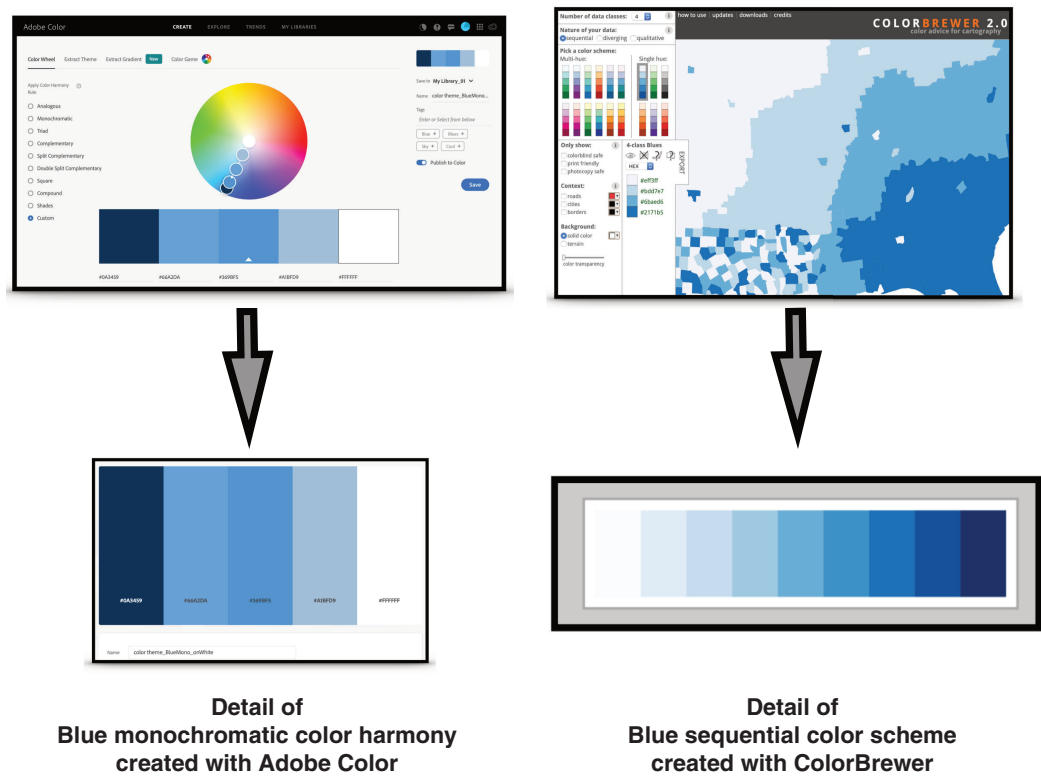


FIGURE 5.3 Comparison of a Blue monochromatic color harmony with a Blue sequential color scheme. Images created by Theresa-Marie Rhyne, 2024, using Adobe Color (<https://color.adobe.com/>) for the Blue monochromatic harmony and ColorBrewer (<http://colorbrewer2.org>) for the Blue sequential sequence.

either for or against an issue with uncommitted responses in the middle are effective uses of diverging color schemes. In Figure 5.5, we show an example of a Pink and Yellow-Green diverging color scheme created with ColorBrewer.

5.4.1 Diverging Color Schemes and Complementary Color Harmonies

The *complementary* color harmony, as featured in Section 4.5.3 of Chapter 4, combines two colors that oppose each other on the color wheel and matches well to diverging color schemes. In Figure 5.6, we show a comparison of a Magenta and Green complementary color harmony with a Pink and Yellow-Green diverging color scheme. The complementary color harmony was created with Adobe Color, while the diverging color scheme was created with ColorBrewer. The color hex codes for both examples are plotted on a color wheel to explore the similarities between color schemes. In addition to serving as a diverging color scheme, the Pink and Yellow-Green scheme from ColorBrewer is also a complementary color harmony.

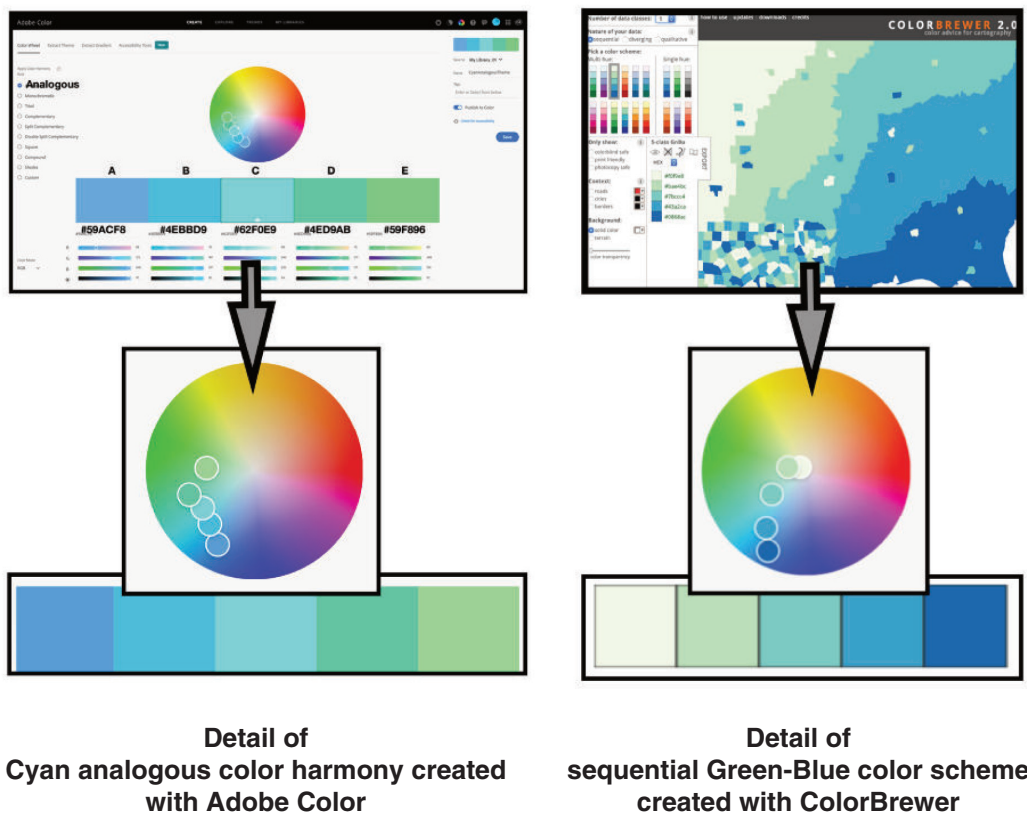


FIGURE 5.4 Comparison of a Cyan Analogous color harmony with a Green-Blue sequential color scheme. Images created by Theresa-Marie Rhyne, 2024, using Adobe Color (<https://color.adobe.com/>) for the Cyan Analogous harmony and ColorBrewer (<http://colorbrewer2.org>) for the Green-Blue sequential sequence.

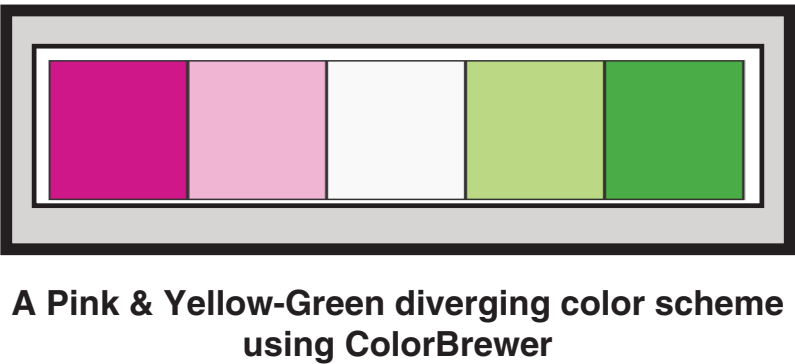


FIGURE 5.5 Example of a Pink and Yellow-Green diverging color scheme. Image created by Theresa-Marie Rhyne, 2024, with elements from the ColorBrewer 2.0 tool, <http://colorbrewer2.org>.

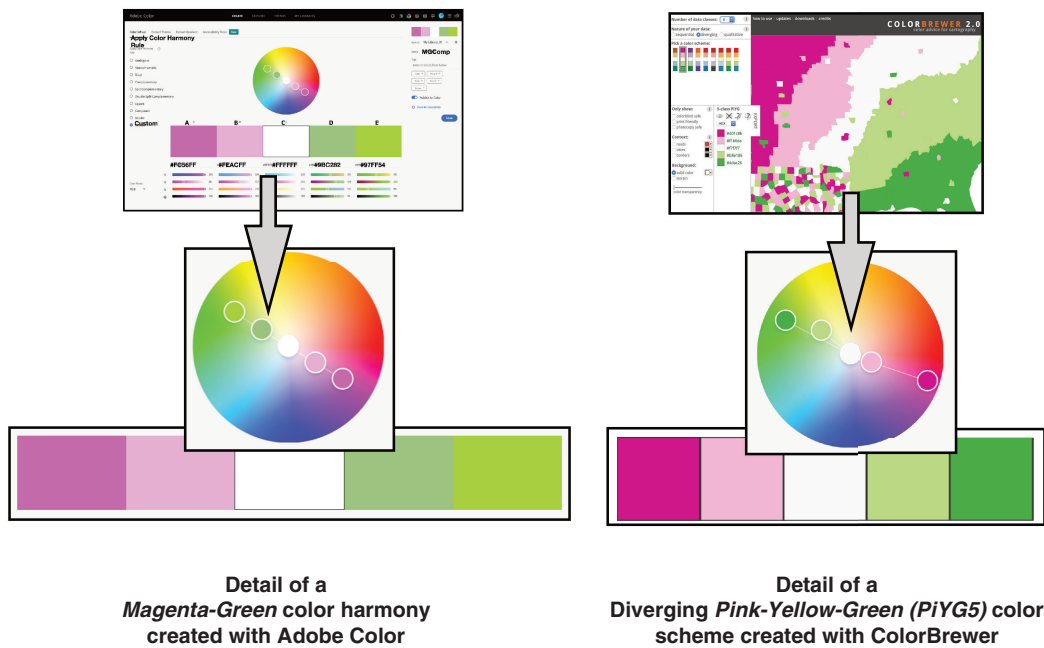


FIGURE 5.6 Comparison of a Magenta-Green complementary color harmony with a Pink-Yellow-Green diverging color scheme. Images created by Theresa-Marie Rhyne, 2024, using Adobe Color (<https://color.adobe.com/>) for the Magenta-Green complementary harmony and ColorBrewer (<http://colorbrewer2.org>) for the Pink-Yellow-Green diverging color scheme.

5.4.2 Diverging Color Schemes That Are Not Complementary Color Harmonies

There are many examples of *diverging* color schemes that are not complementary color harmonies. Two examples that can be created with ColorBrewer are the Purple-Orange and the Red-Blue diverging color schemes. Purple and Orange do not oppose one another on the color wheel to form a complementary color harmony. The same is true for Red and Blue. Figure 5.7 shows these two schemes for five data steps. The color hex codes for both examples are plotted on a color wheel to verify that the color schemes are not complementary.

5.5 THE QUALITATIVE COLOR SCHEME

Qualitative color schemes use colors to label different categories of data. There are no implied magnitude differences between each of the categories. A mapping of different routes on a subway, equivalent steps on a flowchart, or types of vegetables in a market are examples of visualizing qualitative data. There should be no large variances in lightness or saturation of colors since that can signify importance or preference for a particular category. Figure 5.8 shows a detail of a Red, Blue, Green, Purple-Orange, and Yellow 6-step qualitative color scheme extracted from the ColorBrewer 2.0 tool.

In this illustration, we also compare the six-step qualitative color scheme with a very similar color scheme shown as Figure 2.16 in Chapter 2. In Chapter 2, we showed that

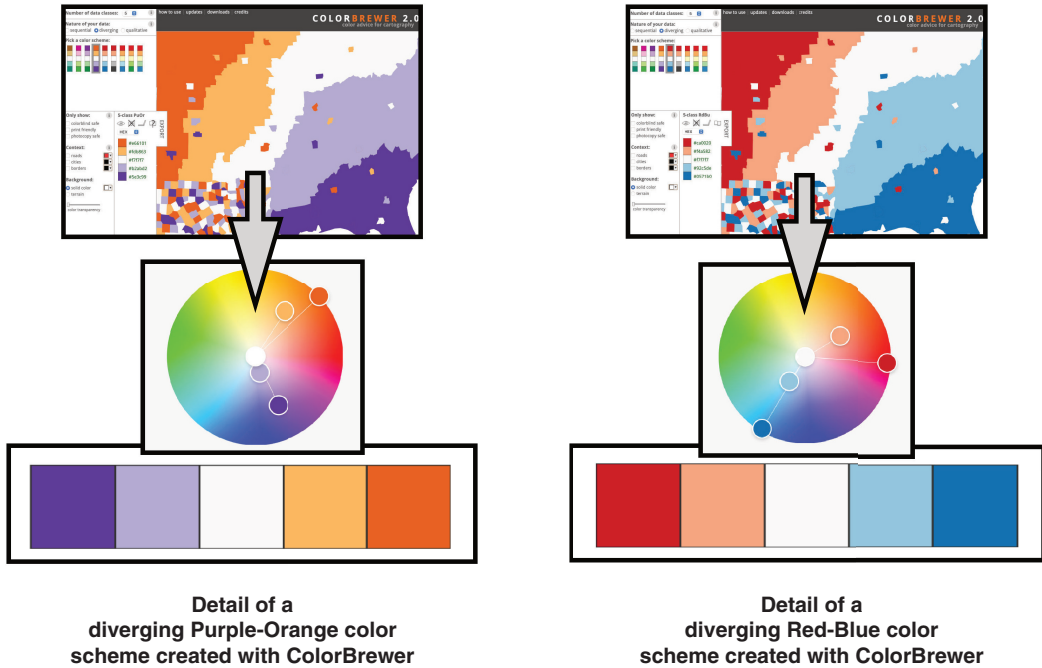


FIGURE 5.7 Two examples of non-complementary harmony diverging color schemes – Purple with Orange and Red with Blue. Images created by Theresa-Marie Rhyne, 2024, with elements from the Adobe Color (<https://color.adobe.com/>) and ColorBrewer 2.0 (<http://colorbrewer2.org>) tools.

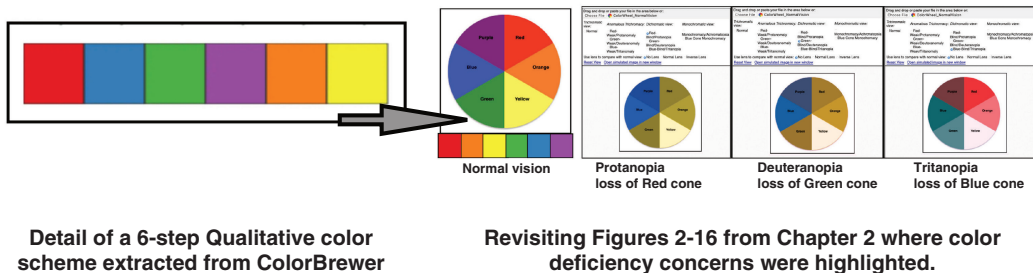


FIGURE 5.8 Detail of a 6-step qualitative color scheme extracted from the ColorBrewer 2.0 tool compared with a similar color scheme from Figure 2.14 that includes color deficiency simulation analyses of the Red, Blue, Green, Purple-Orange, and Yellow colors. Unfortunately, users with color deficiencies could not distinguish between individual colors in the color scheme. This is a risk for qualitative color schemes. Images created by Theresa-Marie Rhyne, 2024, with the 6-step qualitative scheme created with the ColorBrewer 2.0 tool, <http://colorbrewer2.org>.

this Red, Blue, Green, Purple-Orange, and Yellow combination failed color deficiency tests since protanopia (loss of the Red cone), deuteranopia (loss of the Green cone), and tritanopia (loss of the Blue cone) users could not differentiate between individual

elements in the six-stage color scheme. One of the key issues in designing qualitative color schemes is addressing color deficiency. We will revisit these issues later in Section 5.5.3. For now, let's continue to compare color harmonies with qualitative color schemes.

5.5.1 Qualitative Color Schemes and Triad Color Harmonies

The *triad color harmony* is well suited for a qualitative color scheme with three categories of data. As discussed in Section 4.5.9 of Chapter 4, the three colors in the triad color harmony are evenly spaced on the color wheel at 120° apart. This placement produces three distinctive and distinguishable colors with equal variances. Figure 5.9 shows the triad color harmony of Green, Purple, and Orange, based on the RYB color model, converted to a qualitative color scheme, and applied to a donut or ring visualization.

5.5.2 Qualitative Color Schemes and Square Color Harmonies

The *square color harmony* facilitates the building of a qualitative color scheme with four categories of data. As noted in Section 4.5.7.2 of Chapter 4, the four colors in a square color harmony are equidistant at 90° apart on the color wheel and result in two pairs of complements. Figure 5.10 shows the square color harmony of Orange, Yellow, Blue-Green, and Purple, based on the RYB color model. Similar to the triad example, the square qualitative color scheme is applied to a donut or ring visualization. The Paletton Color Scheme Designer (<https://paletton.com>) was used to build and depict this harmony [7]. Chapter 6 will discuss, in further detail, how to use and work with the Paletton Color Scheme Designer and other color suggestion tools.

5.5.3 Color Deficiency Issues for 5-Class Qualitative Schemes and beyond

In general, it is not difficult to build a qualitative color scheme to support up to four distinctive and distinguishable colors that will be considered color-blind safe. As shown in Figures 5.9 and 5.10, the triad and square color harmonies can aid in creating these options. However, as noted by Joachim Goedhart in his writing on “Data Visualization with Flying Colors”, moving to ranges between five and eight colors becomes extremely challenging [8]. After eight colors, even normal color vision individuals find it difficult to distinguish between all colors in the color palette. Interestingly, traditional color harmonies rarely go beyond four distinctive and distinguishable colors as well.

Figure 5.11 explores a 5-class *qualitative color scheme* map example extracted from ColorBrewer. The map example is run through the online Color Blindness Simulator – Coblis, discussed in Section 2.8 of Chapter 2, to check for color deficiencies [9]. The results indicate that individuals with protanopia (loss of the Red cone), deuteranopia (loss of the Green cone), and tritanopia (loss of the Blue cone) are likely to have difficulty distinguishing between the five distinct colors. In situations where qualitative color schemes of five or more colors are used, one approach to address these color deficiency concerns is to enhance the visualization with text or numeric labeling for each color variable. This double coding of data allows for referring to the individual elements by color, number, and label. Chapter 7 will feature case study examples where this concept is used.

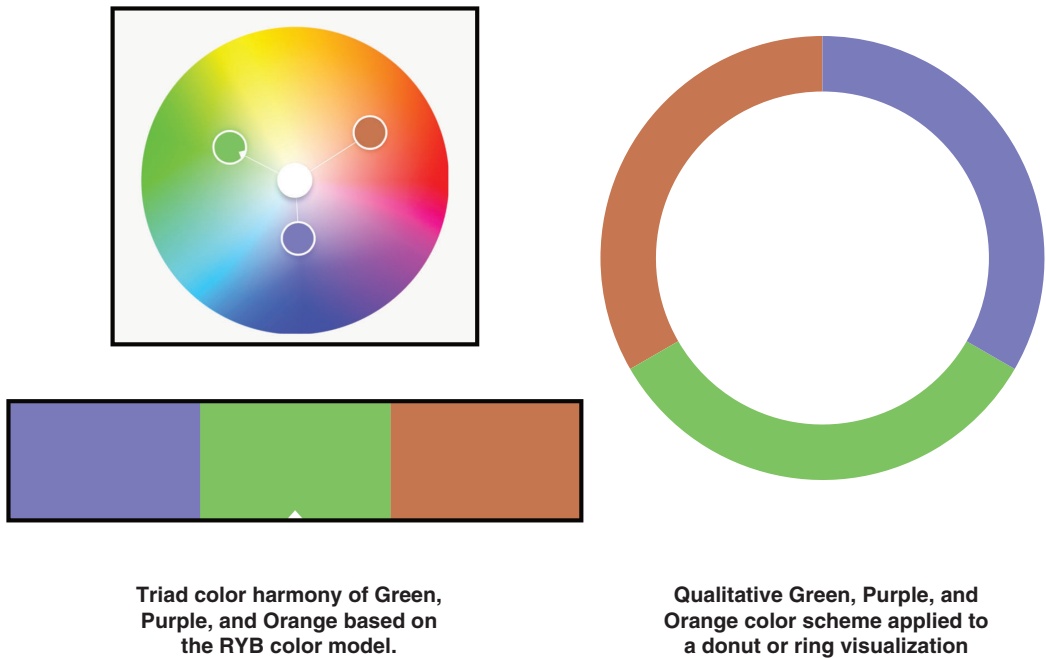


FIGURE 5.9 Detail of a Green, Purple, and Orange triad color harmony converted to a qualitative color scheme and applied to a donut or ring visualization. Images created by Theresa-Marie Rhyne, 2024, using Adobe Color (<https://color.adobe.com/>) for the triad color harmony.

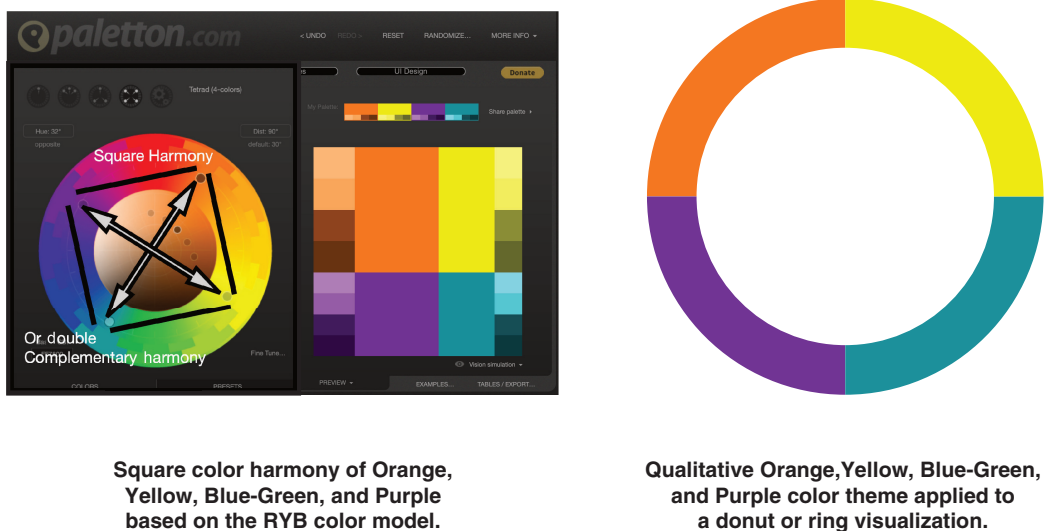


FIGURE 5.10 Detail of an Orange, Yellow, Blue-Green, and Purple square color harmony converted to a qualitative color scheme and applied to a donut or ring visualization. Images created by Theresa-Marie Rhyne, 2024, using the Paletton Color Scheme Designer (<https://paletton.com>) for the square color harmony.

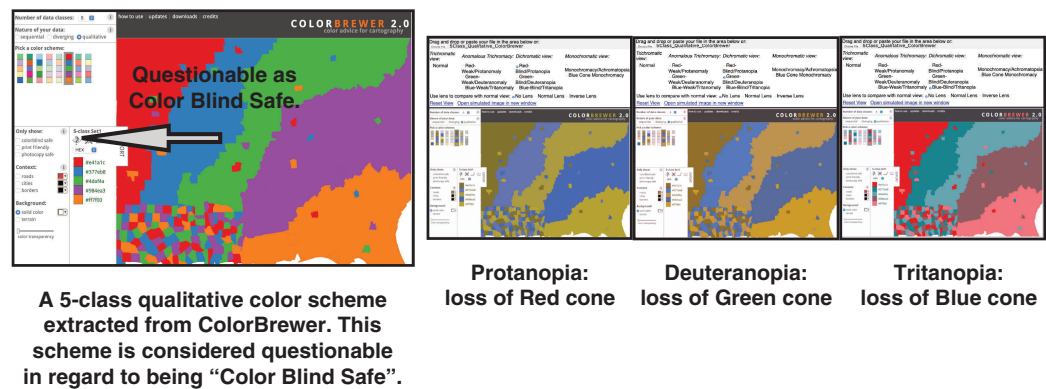


FIGURE 5.11 Color deficiency checks for a map example of a 5-class qualitative color scheme of Red, Blue, Green, Purple, and Orange extracted from ColorBrewer. The scheme is considered questionable regarding individuals with color deficiencies being able to distinguish between each of the five color elements. Images created by Theresa-Marie Rhyne, 2024, with the 5-step qualitative scheme map extracted from ColorBrewer 2.0 (<http://colorbrewer2.org>), and color deficiency simulations executed with Coblis – the Color Blindness Simulator (<https://www.color-blindness.com/coblis-color-blindness-simulator/>).

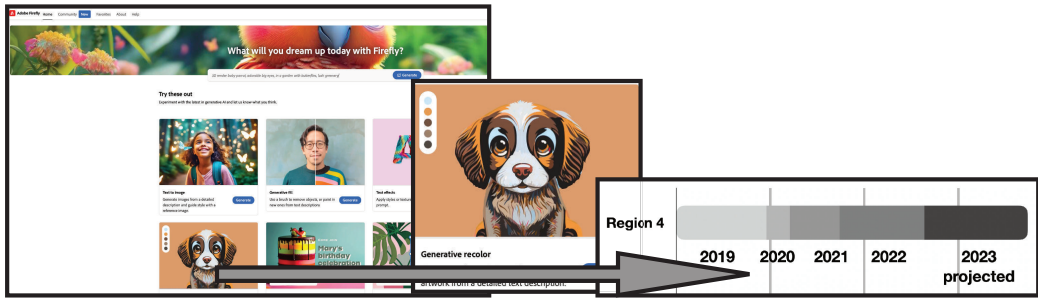
5.6 USING GENERATIVE AI FOR DATA COLOR SCHEMES

Here, we explore the use of generative artificially intelligent (AI) systems to help with color suggestion for data color schemes [10]. A *generative AI* system is a category of artificially intelligent systems that produces new content and ideas by interacting with a user and their requests. The technology dates to the 1960s with interactive systems becoming widely available to the public in 2022. Our queries to these systems are based on understanding the color hex code, color harmony, and data color scheme concepts previously covered in this book. The first example uses *Adobe Firefly*, a creative image-based generative AI system, while the second example interacts with the text-based *ChatGPT* chatbot.

5.6.1 Generating a Sequential Color Scheme with Adobe Firefly

Adobe Firefly is a software collection of generative AI models for building artistic content, <https://firefly.adobe.com>. The online version can provide creative images from text commands that you provide, referred to as prompts [11]. As of September 14, 2023, Adobe released its production version of this generative AI tool that is accessed from the Adobe Firefly website or Adobe’s other creative suite of tools. After setting up an account with Adobe Firefly, a user is allowed 25 free monthly credits to query their system. Additionally, Adobe provides several paid plans for further access to Adobe Firefly, as well as their broad creative suite of tools. A comprehensive review of the functions of Adobe Firefly and how it interacts with other Adobe tools can be found in Reference [12].

For this example of creating a sequential color scheme, we used Adobe Firefly’s “*Generative recolor*” tool to colorize a Scalable Vector Graphics (SVG) image. As of Summer 2024, the “*Generative recolor*” tool was moved to Adobe Illustrator (13). We work though this example here to show how conceptually generative recoloring with SVG files works.



The freely accessible Adobe Firefly Generative AI tool :
<https://firefly.adobe.com>

The “Generative recolor” app that creates color variations of vector artwork from your text descriptions.

Test SVG Grayscale sequential data visualization.

FIGURE 5.12 Adobe Firefly generative artificially intelligent (AI) software collection with a detail of the “Generative recolor” app and test SVG Grayscale sequential data visualization. Composite image created by Theresa-Marie Rhyne, 2024.

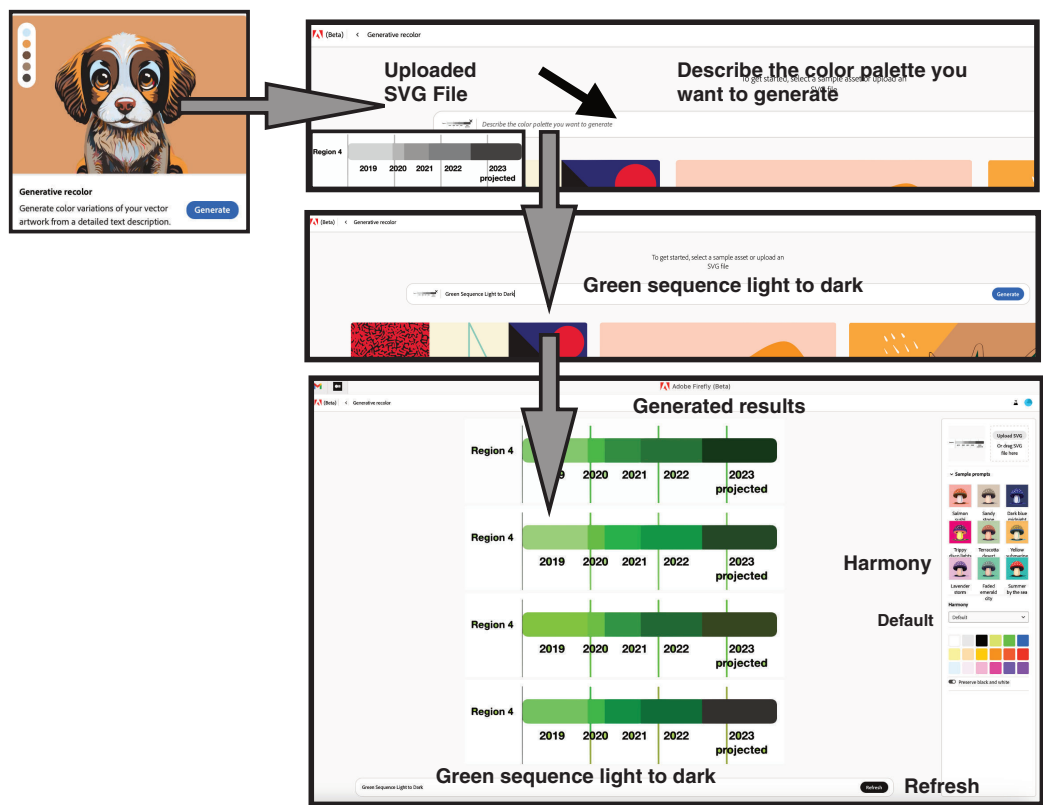
A Scalable Vector Graphics is an open standard developed by the World Wide Web Consortium for defining two-dimensional graphics [14]. Adobe provides a free *Adobe Express* utility for converting an image to an SVG format that was used here [15]. Figure 5.12 shows the Adobe Firefly and Generative recolor tool with our test SVG Grayscale sequential data visualization.

After selecting the “Generative recolor” app from the main Adobe Firefly Web page, we were transferred to another screen that asks for uploading of an SVG file. For our example, the SVG Grayscale sequential data visualization was uploaded. Adobe Firefly then asked us to “Describe the color palette you want to generate”. We typed “Green Sequence Light to Dark” and selected the generate button to obtain four preliminary options. We show this process in Figure 5.13. Notice that Adobe Firefly uses the concepts of color harmonies to recolor SVG files. Although we asked for a single hue of Green, it appears that Adobe Firefly has provided Green options with slight multi-hued variations. This would correspond to the multi-hue sequential sequences discussed in Section 5.3.2 of this chapter and should result in an analogous color harmony.

We chose a favorite Green sequence from the Adobe Firefly options. Next, the Adobe Color app was used to determine the color hex codes and verify our selection to be an analogous color harmony [6]. These results are shown in Figure 5.14. In Chapters 6 and 7, we will discuss how color selection tools, like Adobe Color, can be used to locate the color hex codes and verify the color harmony of generative AI and other color suggestion results.

5.6.2 Building a Portfolio of Diverging Color Schemes with ChatGPT

In Section 3.11.4 of Chapter 3, a demonstration of using the Chat Generative Pre-trained Transformer (*ChatGPT*), <https://chatgpt.com>, to create a Blue sequential color scheme was provided. As a recap, ChatGPT is a text-based generative AI chatbot developed by OpenAI and introduced to the public on November 30, 2022 [16]. Using text-based commands,



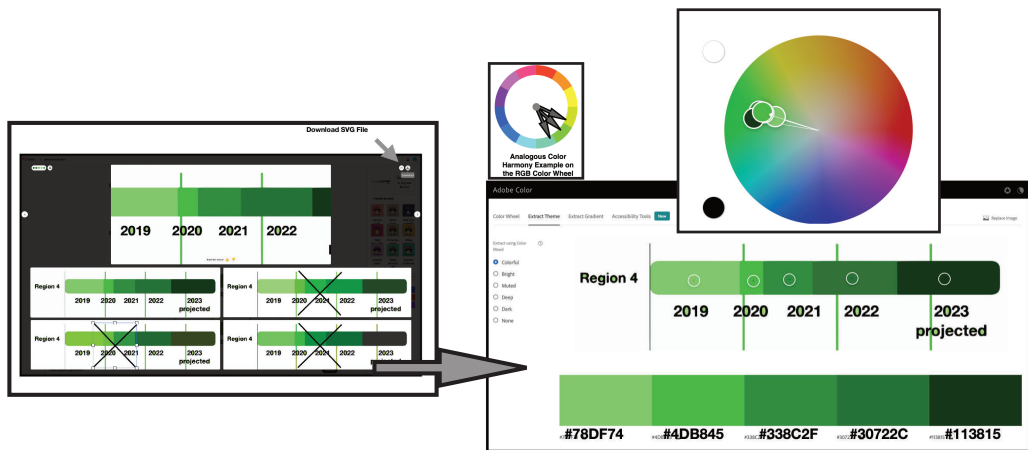
Using Adobe Firefly’s “Generative recolor” app to recolor an SVG Grayscale sequential color scheme.

FIGURE 5.13 Using Adobe Firefly’s “Generative recolor” app to recolor an SVG Grayscale sequential color scheme. Composite image created by Theresa-Marie Rhyne, 2024.

users can ask the chatbot for assistance in tasks such as creating emails, essays, and code. A comprehensive review of the functions of ChatGPT can be found in Reference [17]. The basic version, *ChatGPT 3.5*, is free to use with OpenAI offering a “Plus” version for \$20 a month. We use *ChatGPT* in our example below.

Since ChatGPT is a text-based generative AI model, it does not create or display images directly. However, the chatbot can specify a color scheme based on color hex codes, described previously in Section 3.11.1. Building on data color scheme and color hex code concepts, we challenged ChatGPT to “Create various diverging color scheme suggestions”.

ChatGPT responded with: “Diverging color schemes are often used in data visualization to highlight the contrast between two distinct data points or categories. They typically feature two main colors that are visually distinct and are often separated by a neutral color in the middle. Here are several suggestions for diverging color schemes:”. This response corresponds to the definition of the diverging color scheme described in Section 5.4 of this chapter.



Selecting a favorite Green sequence from the Adobe Firefly options.

Using the Adobe Color app to locate color hex codes and verify the analogous color harmony of selected Adobe Firefly Green sequence.

FIGURE 5.14 Selecting a favorite Green sequence from the Adobe Firefly options and using the Adobe Color app to locate color hex codes and verify the analogous color harmony of the selected Adobe Firefly Green sequence. Composite image created by Theresa-Marie Rhyne, 2024.

ChatGPT then specified eight diverging options with color hex codes noting five classes or steps for each color scheme. The eight schemes were defined as (1) *Blue-Orange diverging*; (2) *Green-Red diverging*; (3) *Purple-Green diverging*; (4) *Red-Blue diverging*; (5) *Yellow-Purple diverging*; (6) *Brown-Blue diverging*; (7) *Pink-Teal diverging*; and (8) *Magenta-Green diverging*. The chatbot ended the response with “Feel free to use these suggestions as a starting point and adjust the colors and shades to suit your specific needs and preferences in data visualization”. The generative AI system also provided the following general comment: “ChatGPT can make mistakes. Consider checking important information”.

The freely available Adobe Color app was used to check and adjust the color hex codes for each ChatGPT diverging color scheme suggestion [6]. Some of the ChatGPT recommendations were inaccurate in terms of systematic color sequencing. Adobe Color facilitated making these corrections. In Chapters 6 and 7, we will demonstrate how to use color selection tools, like Adobe Color, for these types of adjustments to generative AI and other color recommendations. Figure 5.15 shows the original ChatGPT color hex code listing besides the visual “cleaned up” ChatGPT diverging color scheme suggestions produced with Adobe Color.

5.7 CONCLUDING REMARKS

In this chapter, we introduced the concepts of data color schemes that were conceptualized by Cynthia Brewer in her “Color use guidelines for mapping and visualization” writing [1]. There are three classifications of data color schemes: *sequential*, *diverging*, and *qualitative*. Sequential schemes are designed for ordering numeric information where colors progress

ChatGPT diverging color scheme suggestions

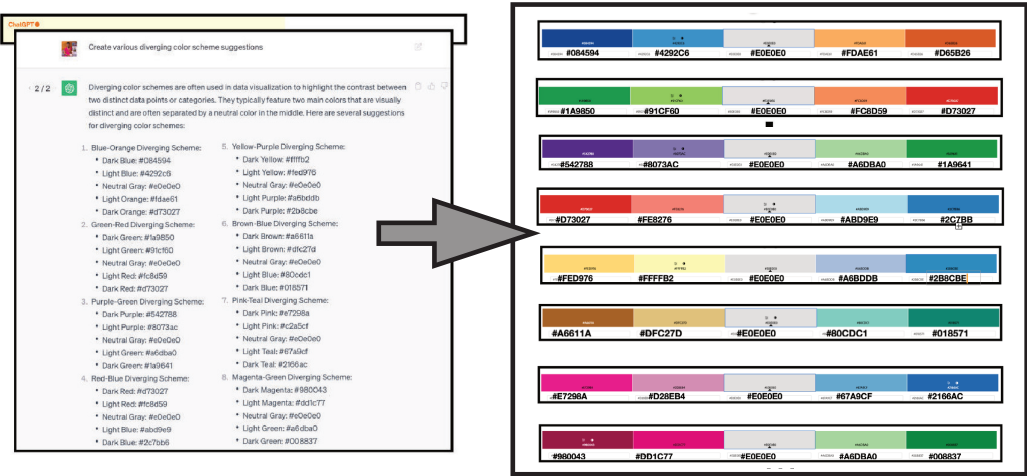


FIGURE 5.15 Comparison of the original ChatGPT color hex code suggestions with the visual mapping of the “cleaned up” ChatGPT diverging color scheme recommendations produced with Adobe Color. Composite image created by Theresa-Marie Rhyne, 2024.

from low to high (or vice versa). Diverging schemes emphasize quantitative data that progresses outward from a central neutral midpoint to two different color extremes. Qualitative schemes are designed for coding categorical information when there is no particular ordering of the data and colors should receive equal perceptual weight. We also demonstrated how the ColorBrewer tool provides color suggestions for each classification. Next, we showed how data color schemes compare to the color harmonies that were discussed in Chapter 4. Color deficiency issues for 5-class qualitative schemes and beyond were also noted. Finally, we highlighted how generative AI tools can assist with data color scheme suggestions. An example of recoloring a Grayscale sequential color scheme with Adobe Firefly was shown. Finally, ChatGPT was used to build a portfolio of diverging color schemes. In Chapter 6, we will discuss in detail online and mobile apps that aid in creating color content and assist in analyzing the color harmony or scheme of an existing digital image.

REFERENCES

1. Brewer, C.A. (1994), “Chapter 7 - Color use guidelines for mapping and visualization”, *Visualization in Modern Cartography*, AM MacEachren, DRF Taylor, eds., 123–147. Tarrytown, NY: Elsevier Science.
2. Harrower, M. and Brewer, C.A. (2003), ColorBrewer.org: An online tool for selecting color schemes for maps. *The Cartographic Journal*, 40 (1), 27–37, <https://www.cs.rpi.edu/~cutler/classes/visualization/S18/papers/colorbrewer.pdf>, accessed March 13, 2024.

3. Makela (2009), “ColorBrewer, Version 2.0”, ArcMap - Arc GIS Blog, <https://www.esri.com/arcgis-blog/products/arcgis-desktop/mapping/colorbrewer-version-2-0/>, accessed March 13, 2024.
4. Brewer, C.A. and Harrower, M. (2024), The Pennsylvania State University and Axis Maps, “ColorBrewer 2.0: Color Advice for Cartography”, <https://colorbrewer2.org/>, accessed March 13, 2024.
5. Munzner, T. (2014), “Chapter 10 - Map color and other channels”, *Visualization Analysis and Design*, A K Peters Visualization Series, 218–241. London, UK: CRC Press.
6. Adobe Inc. (2024), “Adobe Color”, <https://color.adobe.com>, accessed March 14, 2024.
7. Paletton.com (2014), <https://paletton.com/>, accessed March 18, 2024.
8. Goedhart, J. (2019), “Data Visualization with Flying Colors”, The Node, <https://thenode.biologists.com/data-visualization-with-flying-colors/research/>, accessed March 18, 2024.
9. Colblindor (2001), “Color Blindness Simulator”, <https://www.color-blindness.com/coblis-color-blindness-simulator/>, accessed March 18, 2024.
10. Lawton, G. (2023), “What Is Generative AI? Everything You Need to Know”, Tech Target, <https://www.techtarget.com/searchenterpriseai/definition/generative-AI>, accessed March 19, 2024.
11. Adobe Inc. (2024), “Adobe Firefly”, <https://firefly.adobe.com>, accessed August 23, 2024.
12. Cass, J. (2023), “Adobe Firefly Review: The New Generative AI (Detailed Guide)”, Just Creative, <https://justcreative.com/adobe-firefly-review/>, accessed March 20, 2024.
13. Adobe Inc. (2024), “Adobe Illustrator”, <https://www.adobe.com/products/illustrator.html>, accessed August 23, 2024.
14. Lilley, C., Jackson, D., and the SVG Working Group (2004), “About SVG: 2d Graphics in XML”, World Wide Web Consortium, <https://www.w3.org/Graphics/SVG/About.html>, accessed March 19, 2024.
15. Adobe Inc. (2024), “Adobe Express”, <https://new.express.adobe.com/tools/convert-to-svg>, accessed March 19, 2024.
16. Open AI (2022), “ChatGPT 3.5”, <https://chat.openai.com>, accessed March 21, 2024.
17. Dreibelbis, E. (2023), “ChatGPT Review: A Productivity Tool Worth Exploring with Great Caution”, PC Mag.Com, <https://www.pcmag.com/reviews/chatgpt>, accessed March 21, 2024.

Analyzing and Modifying with Online and Mobile Color Tools

6.1 OVERVIEW OF ONLINE AND MOBILE COLOR TOOLS

There are many online and mobile color tools to aid in the process of color scheme design and selection. Now that we have learned the fundamentals of color vision in Chapter 2, principles of color systems in Chapter 3, the language of color harmony in Chapter 4, and reviewed data color schemes in Chapter 5, we now examine how some of these color applications work. Several online tools like the Paletton Color Scheme Designer, ColorBrewer, and hue, chroma, and luminance (HCL) Wizard offer color scheme suggestions. Some online and mobile apps import a digital image of a scene or visualization and evaluate the existing color palette of the image. The Adobe Capture app supports this capability. Adobe Color allows for importing digital images, as well as creating and analyzing a color scheme directly from an RGB/CMYK color wheel. The Viz Palette online app facilitates viewing how generic data visualizations might appear with a given color scheme. The Data Color Picker online tool allows for quickly building sequential, diverging, and qualitative color schemes with specified color hex codes. Many tools incorporate color deficiency checks into their analyses. These include the Adobe Color, Paletton Color Scheme Designer, ColorBrewer, HCL Wizard, and Viz Palette. Other color tools provide minimal automated color suggestion and prefer to allow users to individually select or navigate to the desired colors of choice in the imported image. The COLOURlovers' COPASO online application works in this way. In this chapter, we highlight eight online and mobile color tools to help navigate through the process of color evaluation, suggestion, and application. Our list includes (1) Adobe Color; (2) Adobe Capture; (3) the COLOURlovers community and its Color Palette Software (COPASO) tool; (4) Paletton's Color Scheme Designer; (5) Viz Palette; (6) ColorBrewer 2.0; (7) HCL Wizard; and (8) Data Color Picker.

6.2 ADOBE COLOR

Adobe Color, originally called Adobe Kuler, is an online or Internet application from Adobe Inc. It allows for testing, creating, and saving color schemes that consist of ten colors. Historically, Adobe Color provided for creating schemes with only five colors. In 2024, the tool expanded to include ten colors. Central to the Adobe Color application are an RGB/CMYK color wheel and supporting color harmony options of analogous, monochromatic, triad, complementary, compound, shades, and custom. We covered most of these color harmony types in Chapter 4 of this book. Additionally, the application allows for importing a JPEG or PNG image and automatically selects the key colors in the image. Adobe Color also provides the ability to explore the colors in the imported image, creating your own customized palette of at least ten colors. The online Adobe Color application can be freely experimented with by going to the website <http://color.adobe.com>. An Adobe ID is required to (1) save color schemes for future use; (2) access and share an inventory of color themes created by other members of the Adobe Color community; and (3) integrate Adobe Color palettes with other Adobe Creative Cloud software services such as Adobe Photoshop or Adobe Illustrator. An Adobe ID is free to setup and can be done by going to <https://accounts.adobe.com> (see References [1,2] for additional information on the use of Adobe Color). We work through two examples, which are shown in Sections 6.2.1 and 6.2.2, using Adobe Color. Figure 6.1 shows the Adobe Color user interface with a six-color analogous color harmony in the key of Blue (color hex code #5C5CE6).

Adobe color user interface

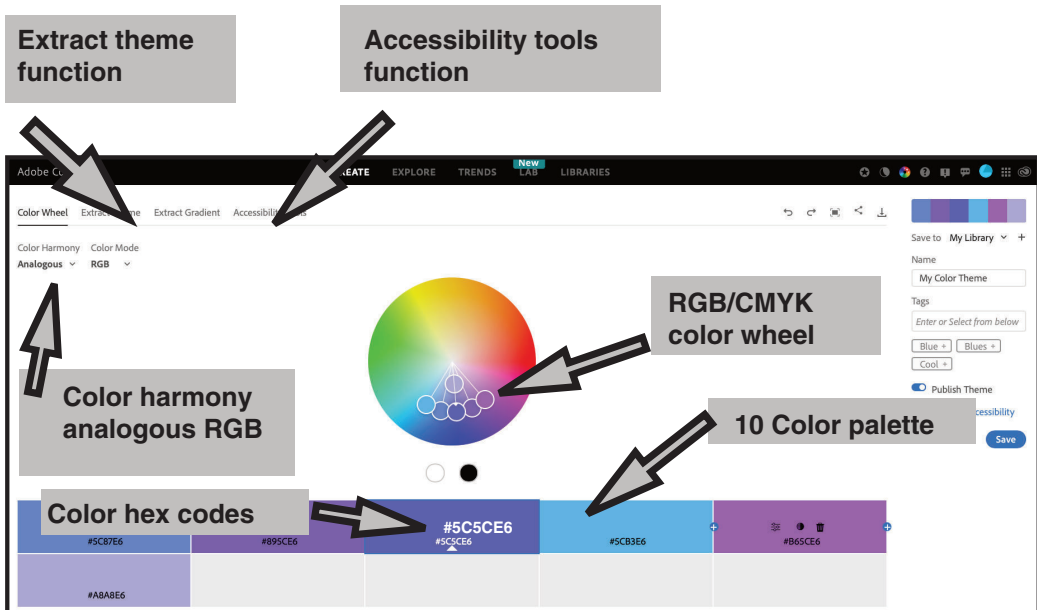


FIGURE 6.1 Adobe Color user interface (<https://color.adobe.com>). Image created by Theresa-Marie Rhyne, 2024, with the Adobe Color tool.

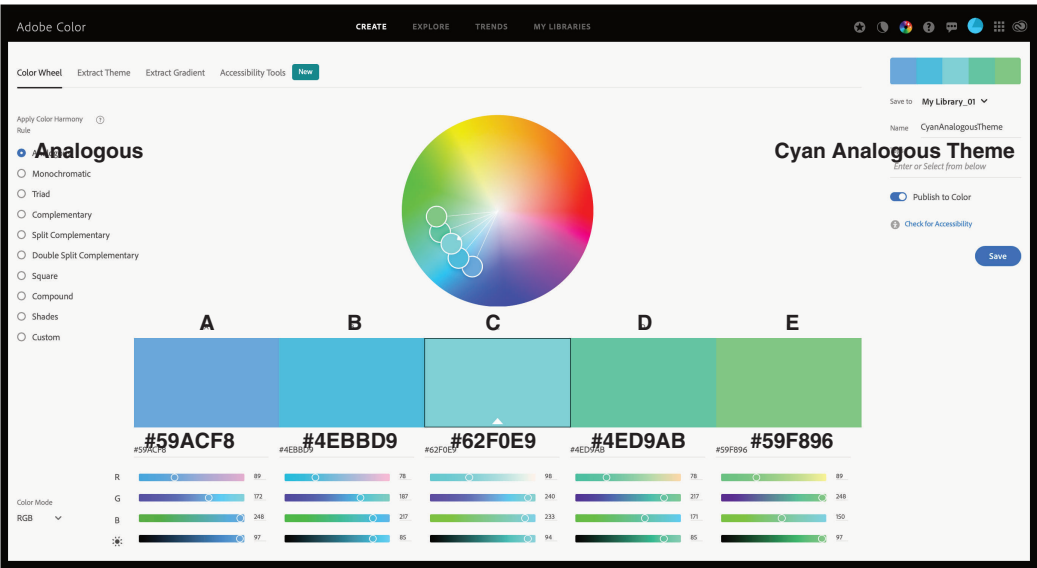


FIGURE 6.2 Entering the key Cyan (#62F0E9) hue as the center color into Adobe Color and selecting the “Analogous” option to create the “Cyan Analogous” color harmony. Image created by Theresa-Marie Rhyne, 2024, with the Adobe Color tool.

6.2.1 Creating Color Schemes with the Adobe Color Wheel

In this first example, Adobe Color is used to automatically calculate an analogous color harmony. Adobe Color defines these as “*color themes*”, like the concept of color schemes. We will use the traditional set of five colors for this effort. This theme was automatically generated in Adobe Color by entering the color hex code of #62F0E9 as the center color and selecting the analogous color harmony. The theme can be named and saved as *Cyan Analogous*. These results are shown in Figure 6.2.

Adobe Color also provides an “*Accessibility Tools*” function that includes protanopia, deuteranopia, and tritanopia color deficiency tests of color themes. This allows preliminary color deficiency tests to be carried out before applying the color harmony to digital media or data visualizations. We discussed these color deficiencies in Section 2.8 of Chapter 2. The results indicate that *Cyan Analogous* theme fails color deficiency tests, and the individual colors need to be repositioned to pass the tests. We adjust colors A, B, and E, as Adobe Color suggests, to produce a *Revised Cyan Analogous* theme that passes color deficiency tests. The original color deficiency tests and the adjusted color theme to pass the tests are shown in Figure 6.3.

As a next step, we apply the *Revised Cyan Analogous* color scheme to building a two-dimensional (2D) stacked bar chart visualization. We used Apple’s Numbers to help generate this example. For the 2D bar chart, only four colors were needed. We used colors B, C, D, and E of the *Revised Cyan Analogous* Adobe Color theme for a new data visualization shown as Figure 6.4.

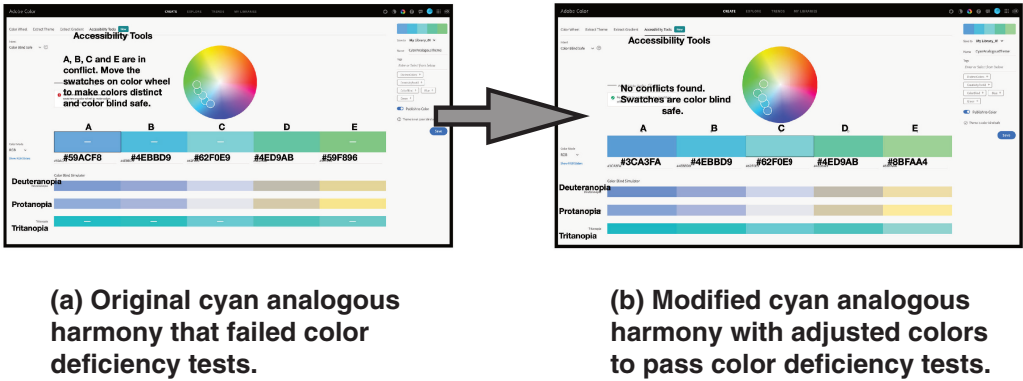


FIGURE 6.3 (a) Preliminary color deficiency checks for the Cyan Analogous color theme using the Accessibility Tools in Adobe Color. The Analogous color scheme fails these tests. (b) Repositioning of color sensors to create a Revised Cyan Analogous theme that passes color deficiency checks. Composite image created by Theresa-Marie Rhyne, 2024, with the Adobe Color tool.

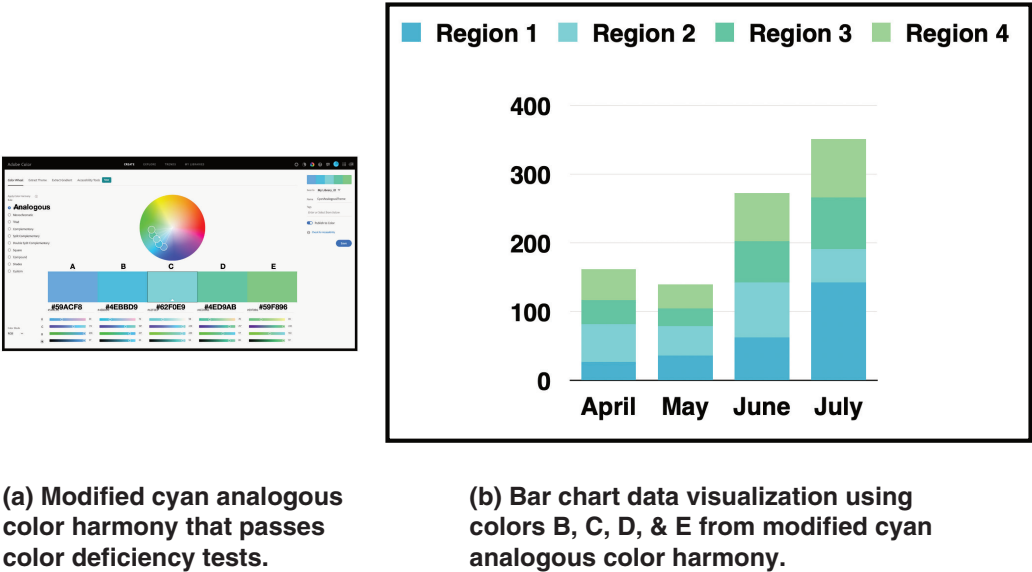


FIGURE 6.4 (a) Revised Cyan Analogous color harmony that passes color deficiency checks and (b) bar chart data visualization using colors B, C, D, and E from Revised Cyan Analogous color harmony. Composite image created by Theresa-Marie Rhyne, 2024.

6.2.2 Capturing a Color Scheme from an Image with Adobe Color

In our second example with Adobe Color, we import a jpeg image into Adobe Color to analyze the colors in the image. Our jpeg image is entitled “Spring Garden” and was the same image used in Section 3.11.5 of Chapter 3 as part of our discussion on Web color selection. As we noted in Section 2.9 of Chapter 2, “jpeg” stands for the Joint Photographic

Workflow for capturing colors in an image with Adobe Color (color.adobe.com)

(1) Import Image, Adobe Color automatically creates color scheme.

(2) Adjust color sensors to desired color scheme.

(3) Check for color deficiency with Accessibility tools. Example passes.

(4) Save & view color scheme to see RGB or color hex codes and possible color harmonies on color wheel.

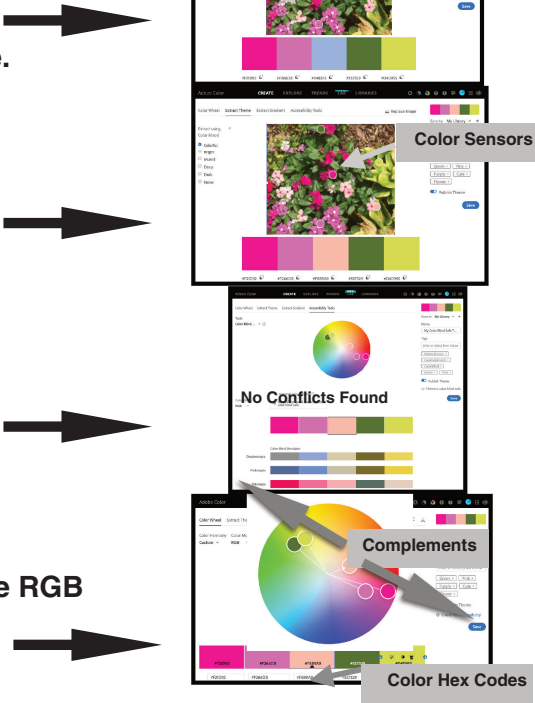


FIGURE 6.5 Workflow depicting the use of the Adobe Color tool (<https://color.adobe.com>) to capture a color scheme from an image. Composite image created by Theresa-Marie Rhyne, 2024, with the Adobe Color tool.

Experts Group (JPEG) and is a frequently used compression format for digital images. In Figure 6.5, the workflow diagram for capturing colors in the image is shown.

In step 1, the jpeg image of “Spring Garden” is imported and Adobe Color automatically creates a color scheme based on a statistical analysis of the top five colors of the image. The selected five colors are displayed as moveable circle sensors on the image. In step 2, the user can modify the proposed color scheme by moving the five color sensors to create a desired color palette. In step 3, check for color deficiency with Accessibility Tools. For our example, the color scheme passes these tests with no conflicts. In step 4, save and view the color scheme to see RGB or color hex codes. An RGB/CMYK color wheel also displays potential color harmonies of the saved color scheme. For our “Spring Garden” color scheme, the Magenta and Green hues are nearly opposing each other on the color wheel. As we learned in Section 4.5.3 of Chapter 4, two colors opposing each other on the color wheel form a complementary color harmony. Therefore, our “Spring Garden” color scheme approximates a complementary color harmony.

6.3 ADOBE CAPTURE

The Adobe Capture app, available for free on Android and iOS platforms, allows for capturing colors from photos on your mobile device. Adobe provides more information at <http://www.adobe.com/products/capture.html>. As noted in the previous discussion on Adobe Color in Section 6.2, a free Adobe ID is required to use Adobe Capture and can be obtained by going to <https://accounts.adobe.com>. Adobe Capture easily imports images from your mobile device's camera or photo library. The app automatically creates a color palette of the five key colors in the image. The five key colors are noted with color sensors that are moveable circles on the imported images. The user can create a custom palette of desired colors by moving the color sensors around on the imported image. The app also has additional functions to create vector graphics, brushes, patterns, and other unique looks from your mobile images. References [3,4] highlight these additional features of the mobile app. Figure 6.6 shows the user interface for capturing color in the Adobe Capture app. We have used a *Luscious Green* photograph taken on a mobile phone as an example.

Clicking on the “circle button with a check mark” yields a *Swatches* option for each of the five color elements. Tapping on each color element yields the color hex codes, RGB numeric specifics, and the brightness value for the selected element. Additionally, there is

Adobe capture app user interface for capturing color

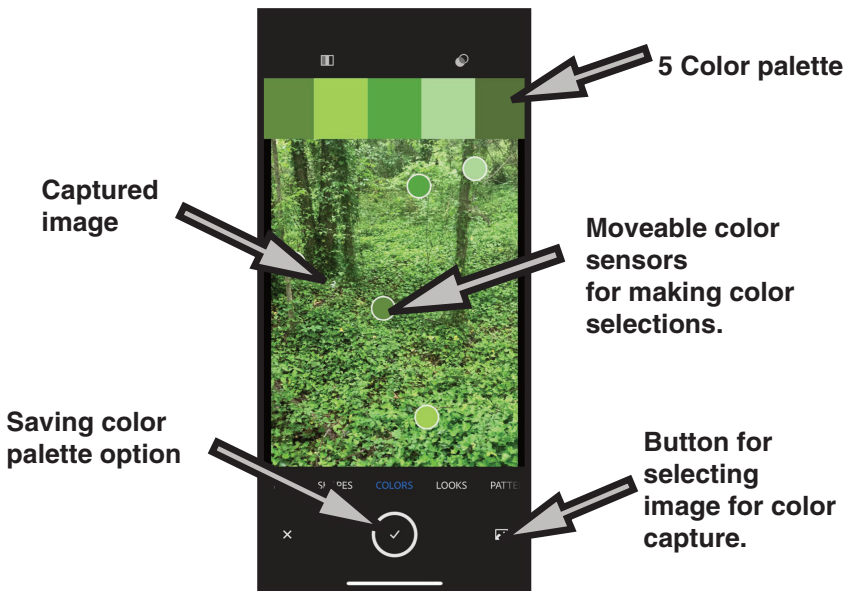


FIGURE 6.6 User interface to the Adobe Capture for capturing color from an image (<http://www.adobe.com/products/capture.html>). Image created by Theresa-Marie Rhyne, 2024, using the Adobe Capture app.

Swatches to harmonies option
In adobe capture

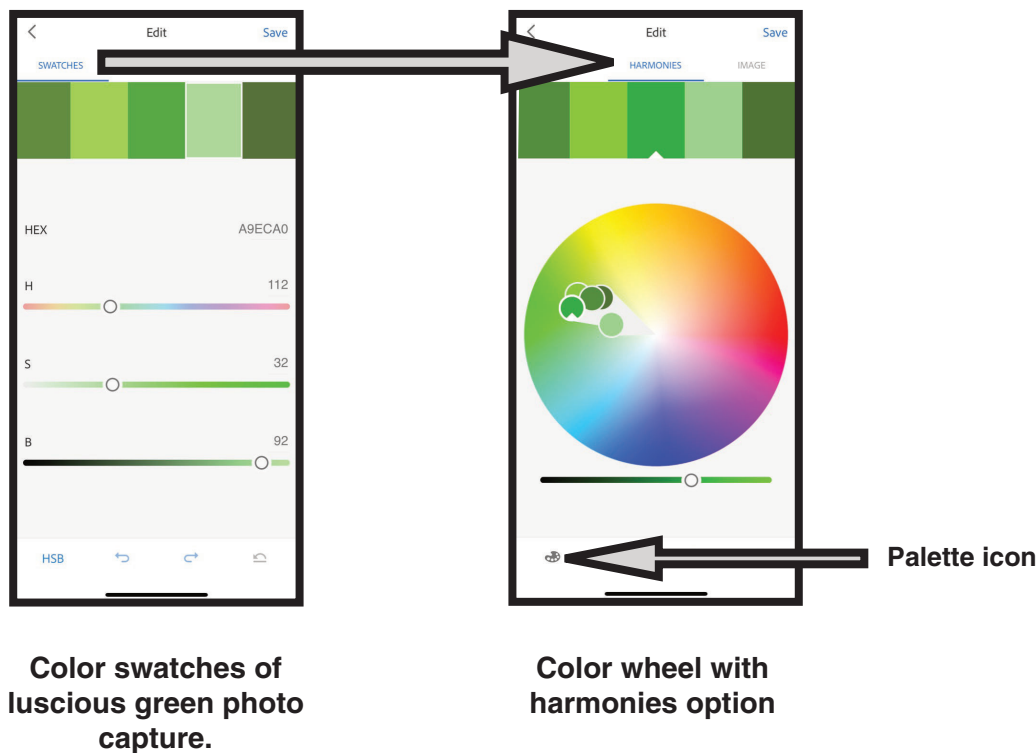


FIGURE 6.7 Transferring from the Swatches to the Harmonies options in Adobe Capture. Image created by Theresa-Marie Rhyne, 2024, using the Adobe Capture app, <http://www.adobe.com/products/capture.html>.

an option entitled *Harmonies* that, when selected, brings up a *Color Wheel* that displays each color element as a circle sensor. Figure 6.7 depicts the process of transferring from *Swatches* to *Harmonies* in the Adobe Capture app.

Clicking on the *Palette* icon in the left-hand corner of the *Color Wheel* screen yields specified color harmonies for *Analogous*, *Monochromatic*, *Triad*, and *Complementary*, as well as *Compound* and *Shades* options. The last option is a *Custom* one for creating your own color harmony. We previously discussed many of these color harmony options in Chapter 4. Figure 6.8 shows the color harmony options available for the extracted *Luscious Green* photograph. Each of the options can be saved in your own online Adobe Color theme library for future use in colorizing digital media [5].

6.4 COLOURLOVERS' COMMUNITY

COLOURlovers.com is a free social network service that focuses on: (1) developing a library of color palettes and patterns created by its user community; (2) discussing color trends in various arenas that apply color; and (3) providing free and helpful online and

Harmonies available in Adobe capture

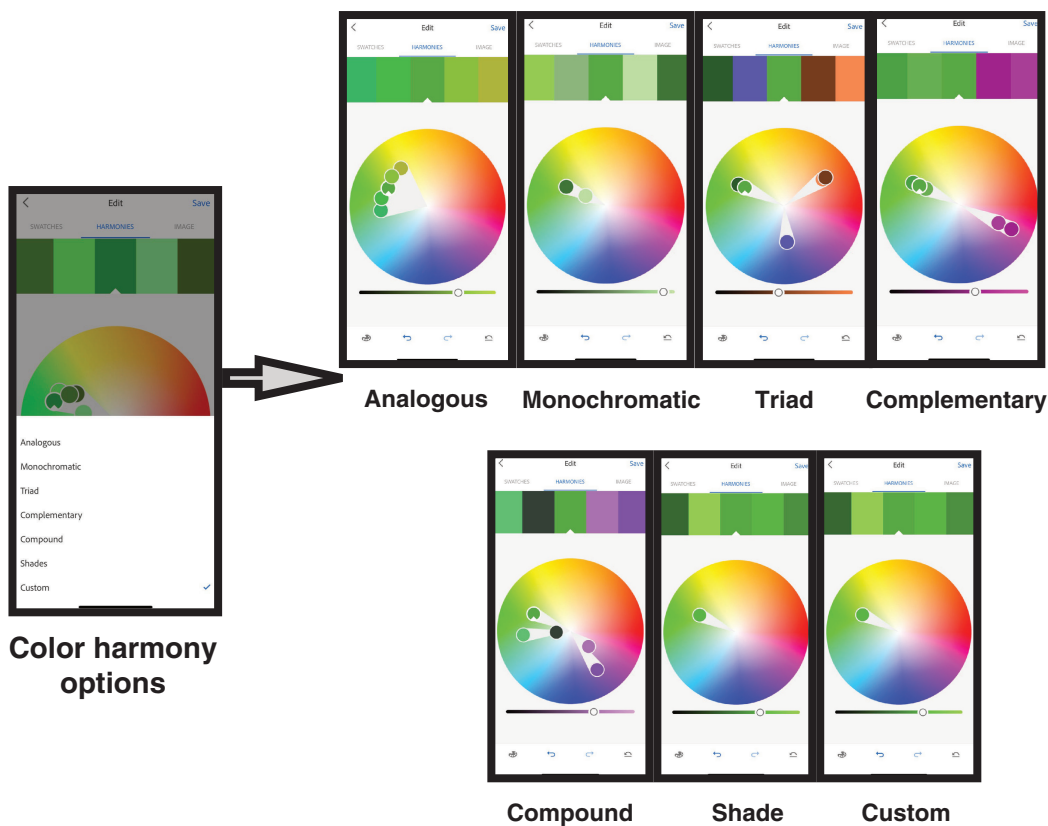


FIGURE 6.8 Adobe Capture specified color harmony options for the extracted Luscious Green photograph. Image created by Theresa-Marie Rhyne, 2024, using the Adobe Capture app, <http://www.adobe.com/products/capture.html>.

app tools for color discovery and analysis. A user joins the COLOURlovers' community by registering and opening an account at <https://www.colourlovers.com/register>. The site indicates that there are over six million colors and two million color palettes available for inspiration and possible usage. Like what we discussed with Adobe Color, COLOURlovers.com provides tools for creating colors and palettes from scratch along with free tools for capturing colors from a pixelated image (see References [6,7] for additional details about the COLOURlovers.com social network). COPASO, Color Palette Software, is the COLOURlovers advanced online color palette tool that allows for creating color schemes from scratch or selecting colors from an uploaded image, <https://www.colourlovers.com/copaso/ColorPaletteSoftware>. Figure 6.9 shows the COPASO user interface.

6.4.1 Creating a Color Palette with COLOURlovers' COPASO

Here, we develop a color scheme, with COPASO, by choosing a Red hue as a base color, and selecting the Tetrad color harmony option in the lower right-hand corner

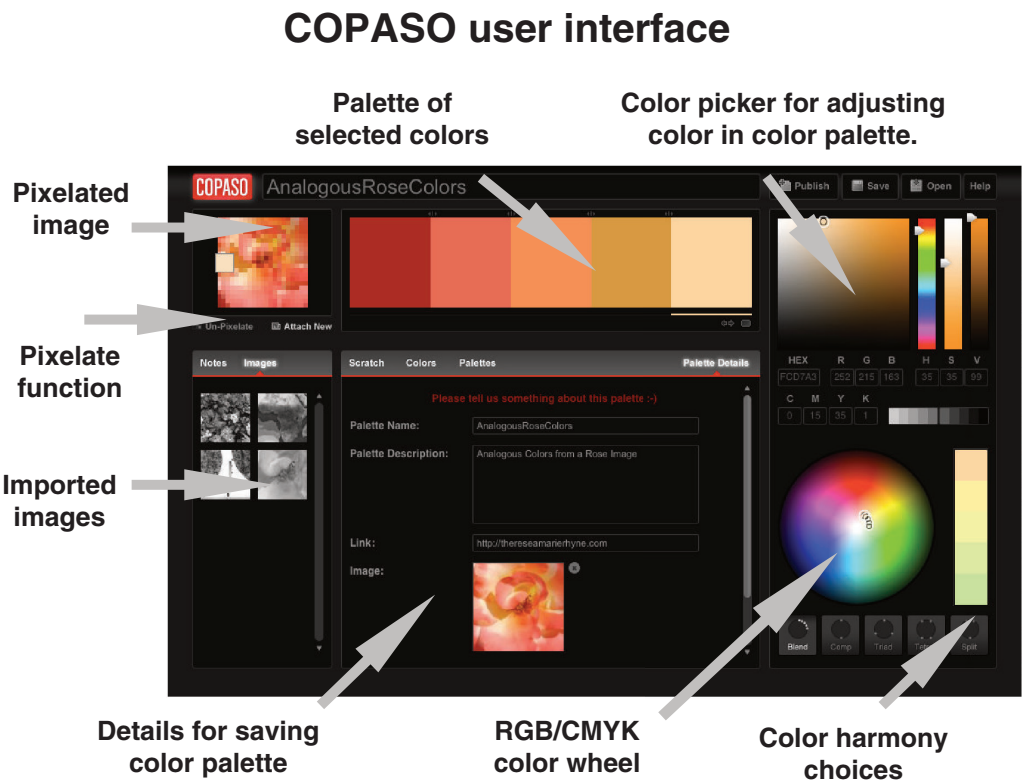


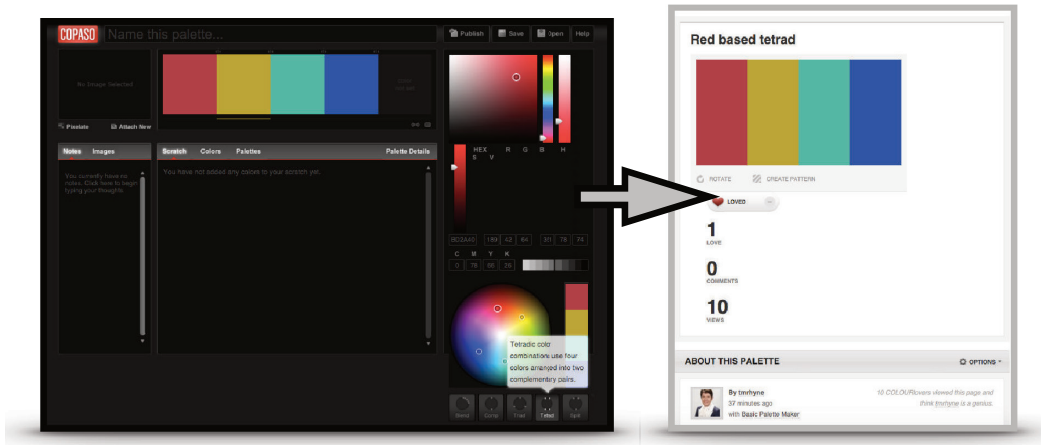
FIGURE 6.9 User interface to the COLOURlovers’ COPASO, Color Palette Software tool, that allows for creating a color palette from either applying color harmony choices or importing a JPEG image. Image created by Theresa-Marie Rhyne, 2024, with the COPASO online tool at the COLOURlovers’ web site, <http://www.colourlovers.com/copaso/ColorPaletteSoftware>.

of the tool. As noted in Section 4.5.7 of Chapter 4, a tetrad harmony encompasses four hues that are equally distant from one another to form a rectangle on the color wheel. Frequently, the result is two complementary pairs of colors. For this example, Red and its opposing or complementary color of Cyan are paired with Yellow and its opposing or complementary color of Blue in the RGB color space. COPASO shows these four colors as dots on its RGB/CMYK color wheel located in the bottom right-hand corner of the application. By selecting a box in the color palette bar at the top of the COPASO application and then double clicking on one of the four tetrad colors recommended by the color wheel in the lower right of COPASO, we are able to enter each suggested tetrad hue to form our color scheme at the top of the COPASO application. We named this color palette “Red based tetrad” and published it on the COLOURlovers site as shown in Figure 6.10.

6.4.2 Capturing a Color Palette from an Image with COLOURlovers’ COPASO

The COPASO application can also be used to capture a color palette from an imported jpeg image. In Figure 6.11, we import the “Spring Garden” jpeg image into COPASO and

COLOURlovers' COPASO online application: Creating a color scheme from a color wheel



Starting with a Red hue and then
applying a tetrad color harmony with
the RGB/CMYK color wheel.

Saved “Red based tetrad”
color harmony / palette on
COLOURlovers' site.

FIGURE 6.10 Building a Tetrad color harmony in the key of Red with the online COPASO (Color Palette Software) tool on the COLOURlovers' website. Image created by Theresa-Marie Rhyne, 2024, with the COPASO online tool at the COLOURlovers' website, <http://www.colourlovers.com/copaso/ColorPaletteSoftware>.

select the “Pixelate” option in the upper left-hand corner of COPASO. After the image is pixelated, we move COPASO's color sensor to select colors for the color palette in the upper center of the application. Once five colors are selected, we name this color palette as “*Spring Garden*” and publish it on the COLOURlovers site as shown in Figure 6.11.

6.5 PALETTON.COM: COLOR SCHEME DESIGNER

Color Scheme Designer is an online resource for recommending color schemes based on artistic color theory and the Red, Yellow, and Blue (RYB) color model noted in Section 1.3 of Chapter 1. While access to the site at www.paletton.com is free, donations are requested to help support the site and keep the resource available online. The application consists of two panels: (1) a color wheel panel for selecting and creating color harmonies on the left and (2) a display panel on the right for assessing how the selected or created color harmony appears. Color Scheme Designer is a robust design tool that includes color harmony suggestions, display views of color schemes including possible Web pages, color deficiency vision simulations, and tables with color hex codes and RGB values for exporting in various formats. We highlight some of the tool's functionality below. References [8,9] provide additional details about this online tool. Figure 6.12 shows the user interface for Color Scheme Designer in the key or base color of Red. This is the default color and hue when Color Scheme Designer is first accessed.

**COLOURlovers’ COPASO online application:
Creating a color scheme from a pixelated image**



**Image imported & pixelated to capture
colors and create Spring Garden
color palette.**

**Saved “Spring Garden”
color palette on
COLOURlovers’ site.**

FIGURE 6.11 Creating a color palette from an image imported and pixelated to capture colors with the online COPASO (Color Palette Software) tool on the COLOURlovers’ website. Image created by Theresa-Marie Rhyne, 2024, with the COPASO online tool at the COLOURlovers’ website <http://www.colourlovers.com/copaso/ColorPaletteSoftware>.

Color scheme designer user interface

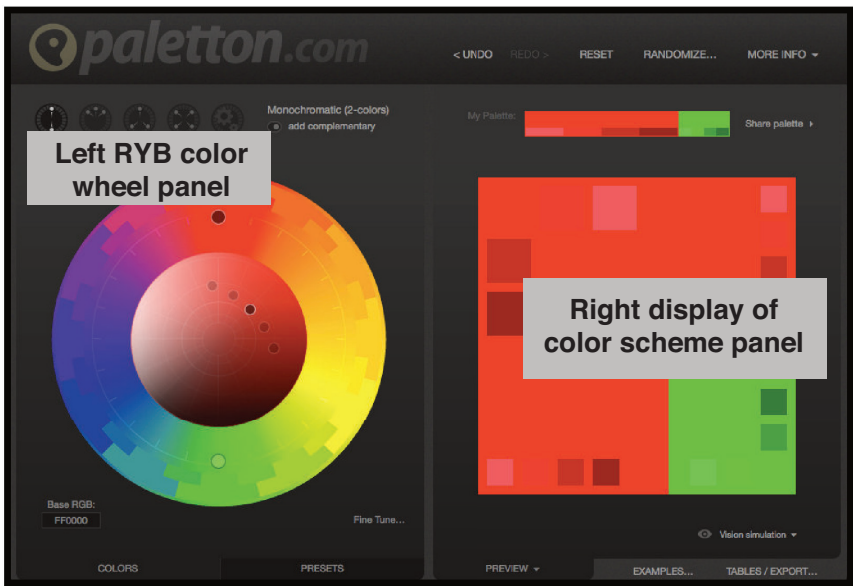


FIGURE 6.12 User interface to the Paletton Color Scheme Designer tool (<http://www.paletton.com>). Image created by Theresa-Marie Rhyne, 2024, with the Color Scheme Designer tool.

Central to *Color Scheme Designer* is a Red, Yellow, and Blue (RYB) painters color wheel displayed in the left panel of this online tool. The use of the RYB color wheel differs from many other similar online tools and apps that use the RGB color wheel. The resulting color harmonies shown with *Color Scheme Designer* are in RYB color space and are the “classic” painter or artistic results. For example, Red is complementary to Green in the RYB color space. However, in RGB and CMYK color spaces, Red is complementary to Cyan. In Chapter 4 of this book, we outlined both the RGB/CMYK and the RYB color wheel and respective color harmonies. For a comparison of RGB/CMYK and RYB color wheel differences, please see Figure 4.4.

6.5.1 Left Panel Color Wheel and Color Selection Functions

In addition to the central color wheel, the left panel also includes (1) color harmony functions in the upper left-hand corner of its color wheel interface; (2) the ability to set a base or key color with a color hex code in the lower left-hand corner of the color wheel; (3) preset color palettes that address tints, tones, and shades of a hue as an option in the lower right-hand corner of its color wheel interface; (4) the capability to fine-tune colors as an option just above the “Presets” function in the lower right-hand corner of the color wheel; and (5) a distribution function in degrees that allows for setting how close the color sensors on the color wheel should be for color harmony functions with multiple hues such as analogous, triad, and tetrad harmonies. We show these options in Figure 6.13.

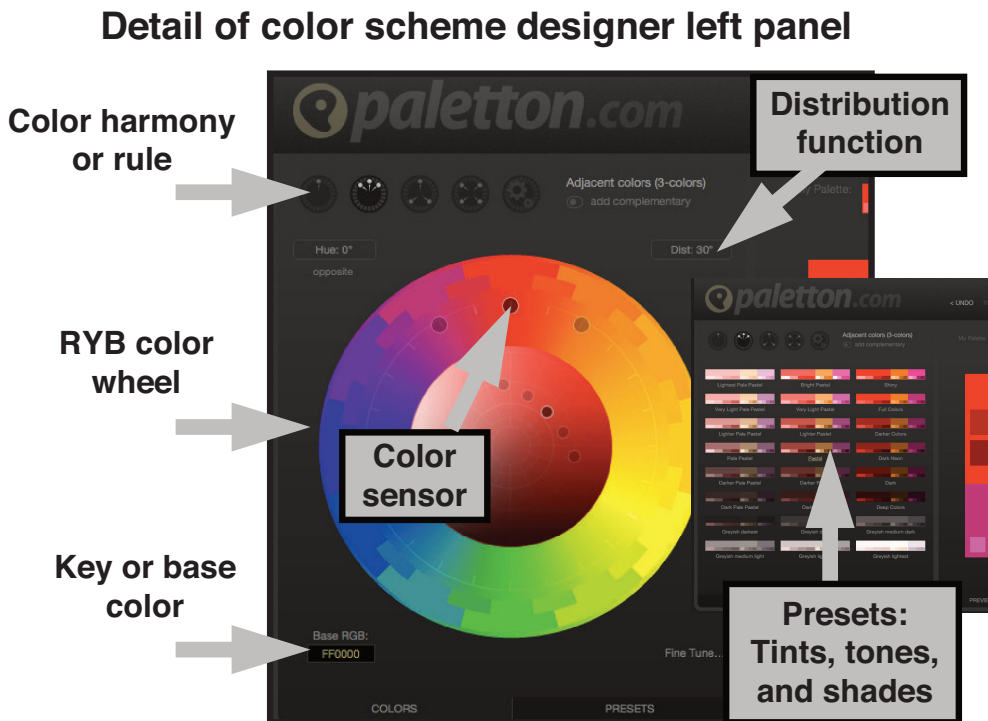


FIGURE 6.13 Details of the left panel of the Color Scheme Designer user interface (<http://www.paletton.com>). Image created by Theresa-Marie Rhyne, 2024, using the Color Scheme Designer tool.

6.5.2 Right Panel Display and Vision Simulation Functions

In the right display panel of the Color Scheme Designer, the selected color scheme or palette is shown. A general overview of the color scheme is displayed at the top of the right display panel. The central display is controlled by the “Preview” option at the bottom left of the right panel. The “Preview” option allows for viewing the color scheme or palette in various display formats noted as *Default*, *Default with text*, *Alternative*, *Alternative with text*, *Circles*, *Mondrianish mosaic*, *Mondrianish mosaic (empty)*, and others. Earlier in this book, we described a color scheme design based on the *Mondrianish mosaic* function in Section 1.6. The “Examples” option, the bottom middle button of the right panel, displays a potential Web page design of the selected color scheme. The “Tables /Export” option, the bottom right button of the right panel, displays the color hex codes and RGB values of the selected color scheme, as well as allows for exporting the color values as code or color swatches to interface with other content creation tools. We show these options in Figure 6.14.

The display panel also includes a “vision simulation” icon that allows for selecting a “color blindness” option such as protanopia (Red cone), deuteranopia (Green cone), tritanopia (Blue cone), and other color deficiencies. We covered these and other specific color deficiencies that Color Scheme Designer supports in Section 2.8. We show a Color Scheme Designer vision simulation for Red cone or protanopia deficiency in Figure 6.14.

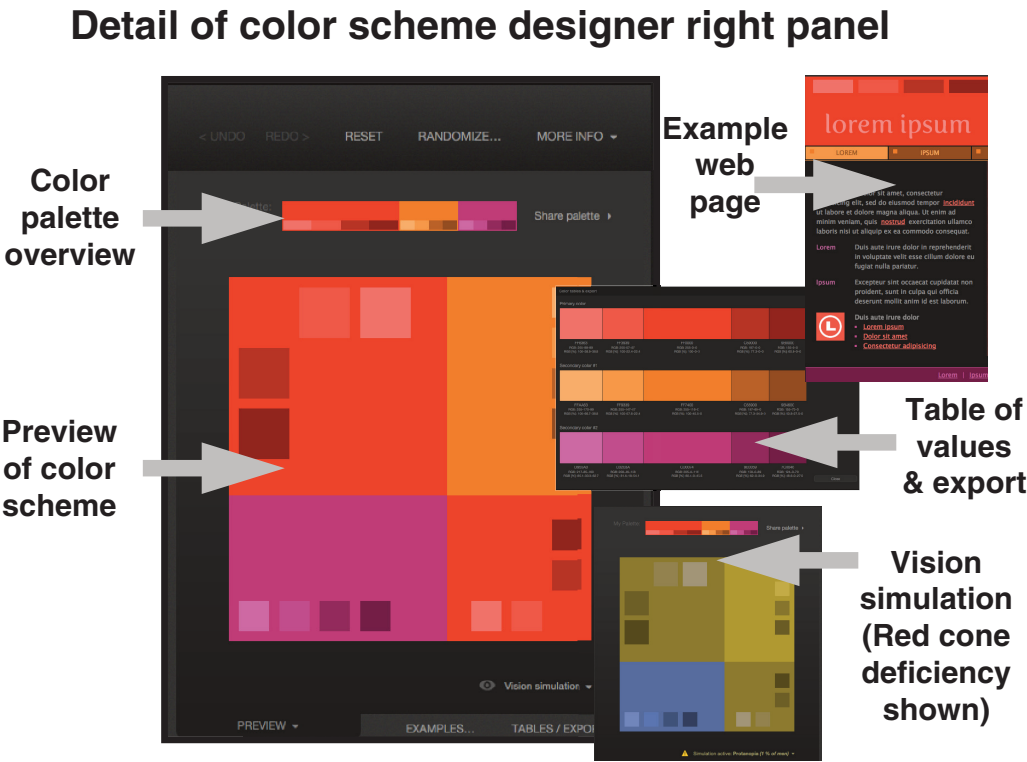


FIGURE 6.14 Details of the right panel for the Color Scheme Designer user interface (<http://www.paletton.com>). Image created by Theresa-Marie Rhyne, 2024, using the Color Scheme Designer tool.

6.5.3 Selecting and Implementing a Square – Tetrad Color Scheme

In Section 5.5.2 of Chapter 5, we showed a square color harmony created with the Paletton Color Scheme Designer. Here, we discuss how to build that harmony. As our first step, we chose the “Alternate” view from the “Preview” function in the right panel of Color Scheme Designer. This allows us to view hues, tints, tones, and shades of the colors we select. Next, we begin working with the RYB color wheel in the left panel to select our key or base color as Orange. To do this, we move the color sensor to the Orange region of the color wheel and notice that we have a monochromatic color scheme. Orange hues, tones, and shades should appear in the right display window. Next, we select the Tetrad (4 colors) function to find three additional colors with Orange. The complement to Orange, Blue-Green, on the RYB color wheel is automatically shown to us. The two other colors are Light Orange and Dark Blue.

We move the Dark Blue color sensor into the Purple regions of the color wheel and set a *Dist* (distribution) value equal to 90° to create a square (tetrad) color scheme. The complement to Purple is Yellow on the Color Scheme Designer’s RYB color wheel. As a result, we have two complementary pairs of Orange and Blue-Green with Purple and Yellow. These colors appear in the right display window panel in Color Scheme Designer as our tetrad (four-color) scheme. To view a vision simulation for Red cone deficiency or protanopia, we select that option from the “Vision Simulation” tab in the lower right-hand corner of the right display panel. The vision simulation indicates us that if we stay with the hue values, there will be a sufficient difference between the four colors. The hues of Orange and Yellow will look slightly different to someone with the protanopia color deficiency with Orange appearing to be a darker shade of Yellow. Next, we select the Tables/Export function in the right display panel to view and export the hue values in the color hex code or RGB format. The four colors are the key of Orange #FF7800, Blue-Green #028E9B, Purple #7608AA, and Yellow #F8FE00. Figure 6.15 provides a summary flowchart of each of these steps for creating a square harmony in the key of Orange #FF7800.

Now that we have the color hex codes and RGB values of our four hues, we can use our color scheme for design purposes. For our example, we use the sample data set of sales over a 4-month period applied to color harmony examples in Chapter 4 to create a data visualization. We decide to build a two-dimensional stacked bar chart, created with Apple’s Numbers and Pages software. The respective protanopia, deuteranopia, and tritanopia color deficiency tests for the bar chart visualization are also shown. Figure 6.16 summarizes our efforts.

6.6 VIZ PALETTE: A TOOL FOR VIEWING DATA VISUALIZATION EXAMPLES OF COLOR SCHEMES

Viz Palette is a free color assessment tool for exploring how color scheme designs might appear when applied to generic data visualization examples. It was created by Elijah Meeks and Susie Lu and is available at <https://projects.susielu.com/viz-palette?colors=%5B%22#ffd700%22,%22>. As Elijah Meeks notes, it was designed to interface with several data color

Using color scheme designer:
Creating square - tetrad (4 color) scheme

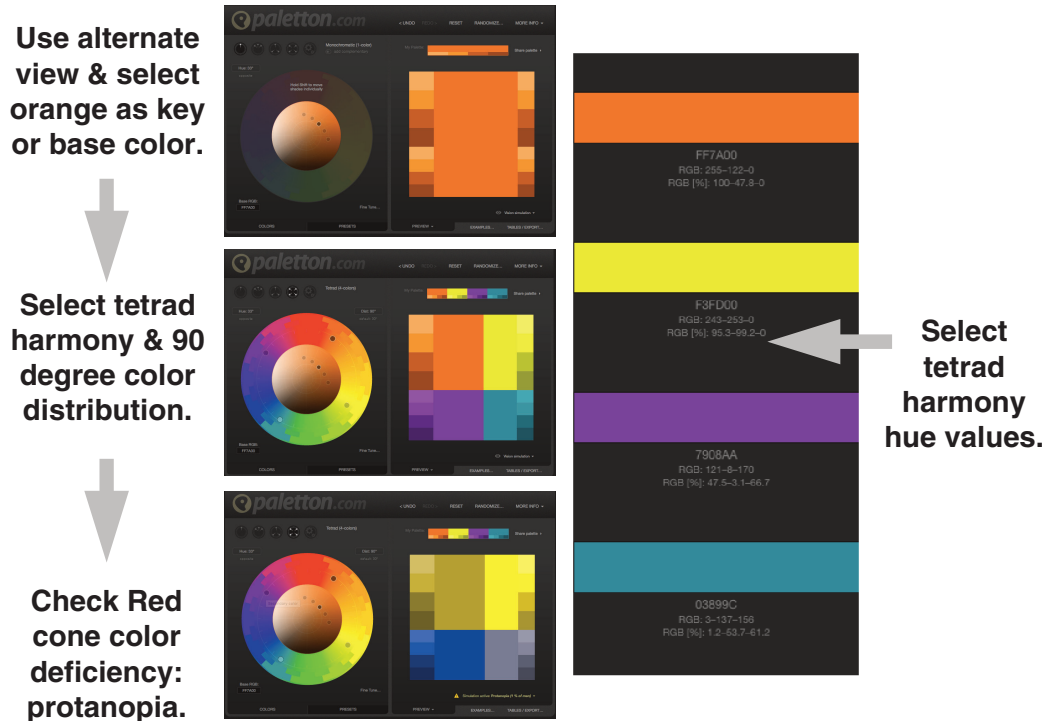


FIGURE 6.15 Workflow diagram for using the Paletton Color Scheme Designer tool (<http://www.paletton.com>) to create a square tetrad color scheme in the key or base color of Orange #FF7800. Image created by Theresa-Marie Rhyne, 2024, using the Color Scheme Designer tool.

scheme research efforts [10]. The app also includes color deficiency tests for Red cone (e.g., protanopia) and Green cone (e.g., deuteranopia) color deficiencies since this represents 99% of this population [11]. We have found that entering the color hex codes of a test color scheme directly into Viz Palette is one of the most effective ways to use the tool. Figure 6.17 shows the Viz Palette use interface.

We can use the four colors from the square – tetrad color scheme developed in Section 6.5.3 to see Viz Palette in action. Our first step is to enter the color hex codes for this “Orange Squared” color scheme. These are Orange #FF7800, Blue-Green #028E9B, Purple #7608AA, and Yellow #F8FE00. After the color hex codes are entered, Viz Palette automatically creates generic visualization examples with the default *No Color Deficiency* menu option. We can also check for color deficiencies by selecting options across the upper menu bar under *Colors In Action*. Figure 6.18 shows results from these efforts where the normal vision, protanopia, and deuteranopia Viz Palette options are explored. Like the results in Section 6.5.3, the Viz Palette color deficiency tests indicate that for the specified “Orange Squared” color scheme, there will be a sufficient difference between the four colors for individuals with protanopia and deuteranopia to distinguish between each color element.

Square (4 hues) scheme: Normal & color deficiencies created with color scheme designer

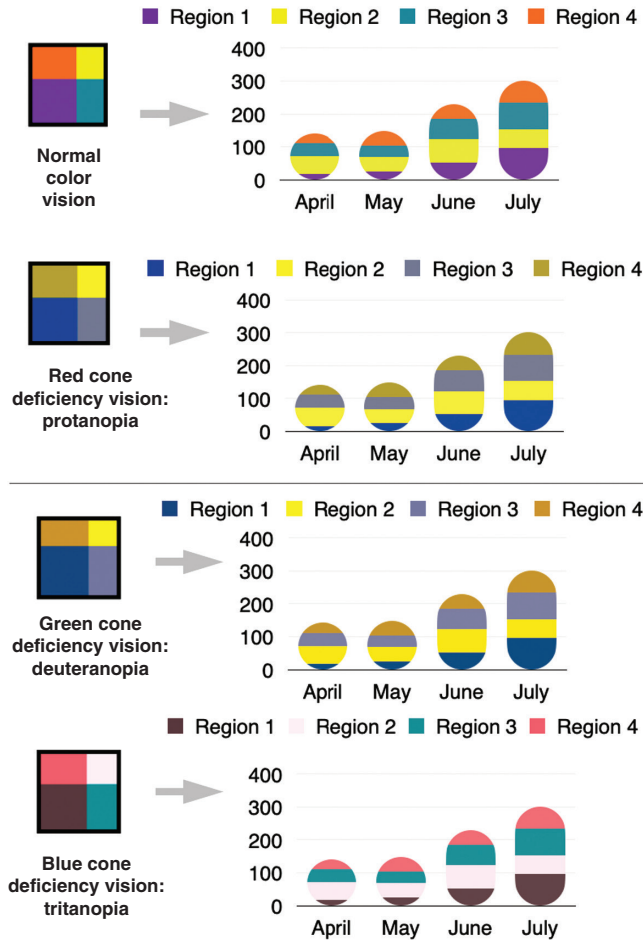


FIGURE 6.16 Applying the square – tetrad color scheme in the key of Orange #FF7800 to the development of a 2D stacked bar chart with four colors. For this example, we also include the 2D stacked infographic with hues of the Color Scheme Designer’s protanopia, deutanopia, and tritanopia vision simulations to help us visualize the color deficiency perspectives of the infographic. Image created by Theresa-Marie Rhyne, 2024, using the Paletton Color Scheme Designer tool, <http://www.paletton.com>.

6.7 COLORBREWER 2.0 REVISITED

In Chapter 5, the concept of data color schemes, as conceptualized by Cynthia Brewer, was discussed. There are three classifications of data color schemes: *sequential*, *diverging*, and *qualitative*. Sequential schemes are designed for ordering numeric information where colors progress from low to high (or vice versa). Diverging schemes emphasize quantitative data that progresses outward from a central neutral midpoint to two different color extremes.

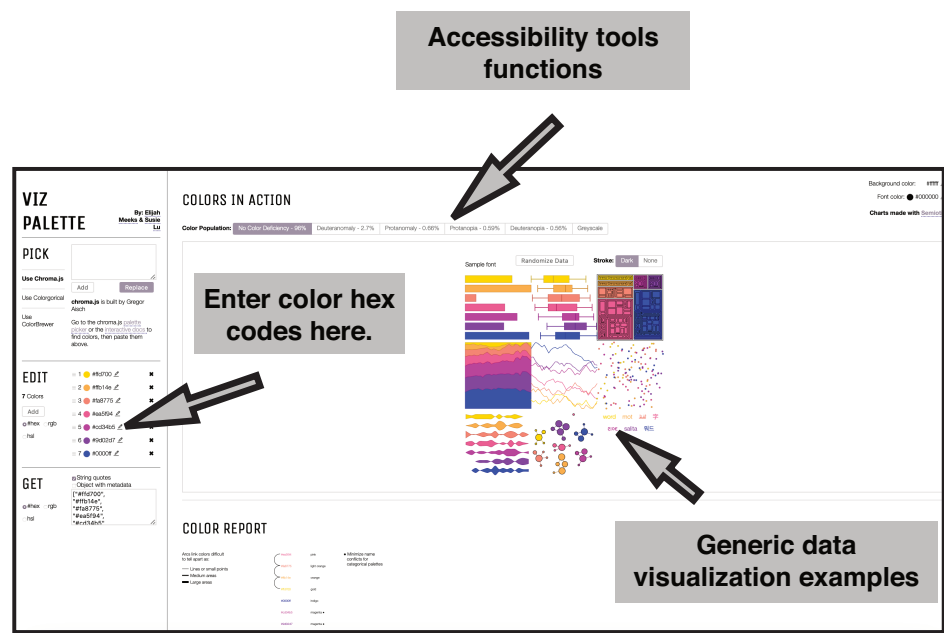


FIGURE 6.17 The Viz Palette user interface (<https://projects.susielu.com/viz-palette>). Image created by Theresa-Marie Rhyne, 2024, with the Viz Palette tool.

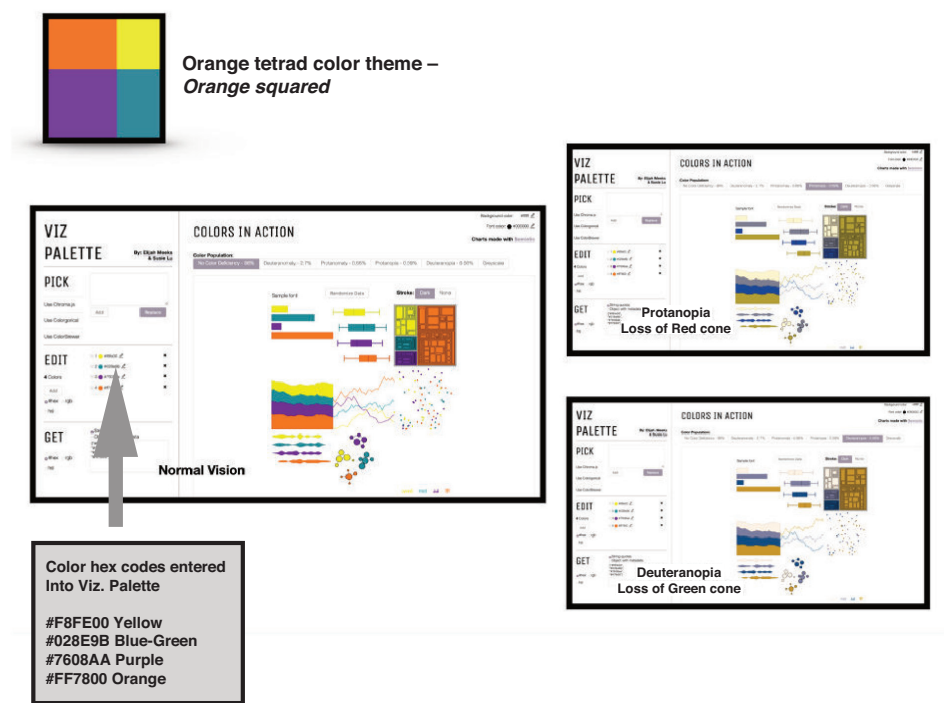


FIGURE 6.18 Entering colors from the Orange square – tetrad color scheme, developed in 6.5.3, into Viz Palette to explore generic data visualization examples, as well as protanopia and deuteranopia color deficiencies for these examples. Image created by Theresa-Marie Rhyne, 2024, with the Viz Palette tool, (<https://projects.susielu.com/viz-palette>).

Qualitative schemes are designed for coding categorical information when there is no particular ordering of the data and colors should receive equal perceptual weight. See Figure 5.1 for a diagram of these concepts.

Here, we show how to use the ColorBrewer online resource (<http://colorbrewer2.org>) that actualizes these concepts [12,13]. As indicated by its geographic map like user interface, ColorBrewer was initially designed as “color advice for cartography” with Cynthia Brewer authoring several books on geographic map design since ColorBrewer’s introduction [14]. ColorBrewer 2.0 has gone beyond its original intent with wide usage in the infographic and data visualization communities. Many ColorBrewer color schemes are now incorporated into several Geographic Information System (GIS) and data visualization tools with appropriate credit given to the ColorBrewer project [15].

When ColorBrewer 2.0 is accessed online, the application appears with a set of selection items on the left and a cartographic map with borders drawn on the right. The default setting is the “*sequential*” and “*Multi-hue*” Blue-Green (noted as *BuGn*) color scheme. The default *Context* is *borders*, referring to the outlines of a map. The first step in using ColorBrewer requires determining the “*Number of data classes*” or the number of variables you want to display with a given chart or map. ColorBrewer starts with 3 as the lowest number of data classes. The next step with ColorBrewer is to select the “*Nature of your data*” or the kind of color palette desired. These are the sequential, diverging, and qualitative color scheme choices. The next step is to select a desired color scheme or palette among the various options provided. Figure 6.19 shows the default user interface to ColorBrewer 2.0 that comes up when the tool is selected at <http://colorbrewer2.org>.

ColorBrewer provides additional options for customizing your color selection process. The “*Only Show*” items include “*colorblind safe*”, “*print friendly*”, and “*photocopy safe*”. As noted earlier, for developing a map, the “*Context*” items include “*roads*”, “*cities*”, and “*borders*”. The default selection includes “*borders*” as checked. It is often helpful to unselect the “*borders*” option so that the cartographic map on the right displays the color scheme without the border boundaries. The “*Background*” menu allows for selecting “*solid color*” or “*terrain*”. The default item is “*solid color*”, and that is the most often used selection from the “*Background*” menu. The “*terrain*” function allows for seeing a three-dimensional map terrain underneath the selected color scheme. Once a color scheme is selected, ColorBrewer notes it. In Figure 6.19, the default 3-class Blue-Green color scheme is noted as “*3-class BuGn*” in the menu bar in the lower left corner, adjacent to the cartographic map display. This menu section has icons that note if a color scheme is “*color blind safe*”, “*photocopy friendly*”, “*laptop or LCD friendly*”, and “*printer friendly*”. The menu button allows for selecting color hex codes, RGB, and CMYK values. The color hex codes are the default option. The “*Export*” function allows for sharing and exporting the selected color scheme data as: (1) a direct Web URL to the selected color scheme; (2) an Adobe color scheme file format for usage with Adobe creative tools; (3) a GIMP color palette; and (4) a Cascading Style Sheet format for further Web development efforts.

ColorBrewer 2.0: Default user interface

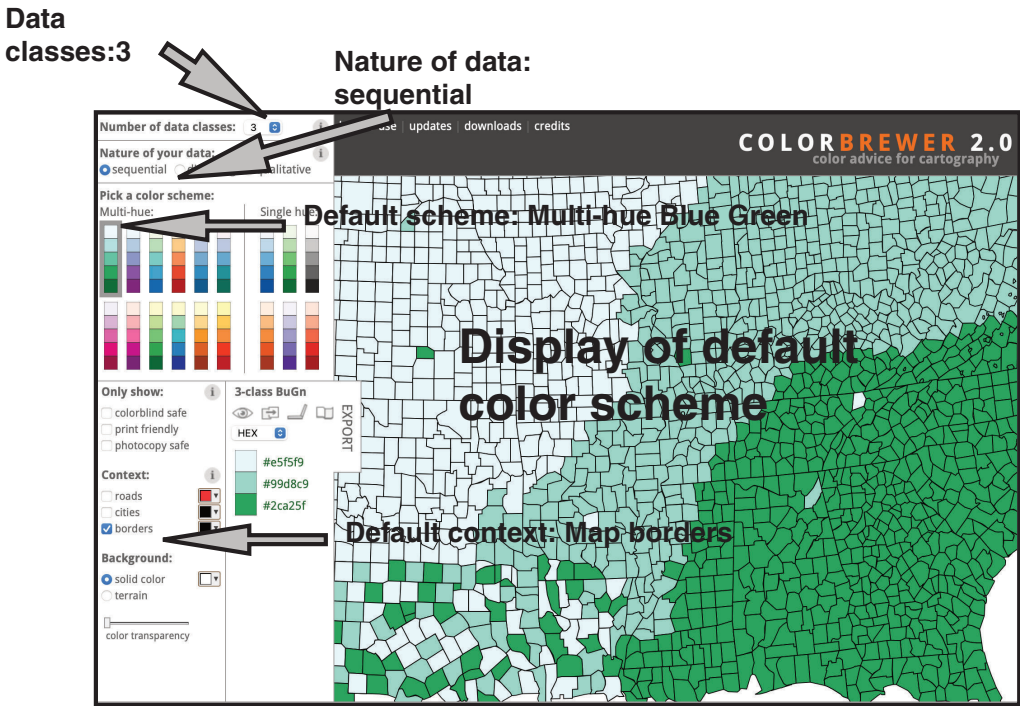


FIGURE 6.19 Default multi-hue Blue-Green (BuGn) sequential color scheme and interface to ColorBrewer 2.0 that comes up when the tool is accessed at <http://colorbrewer2.org>. Image created by Theresa-Marie Rhyne, 2024, with the ColorBrewer 2.0 tool.

6.7.1 Selecting a Qualitative Color Scheme with ColorBrewer

We work through an example here to illustrate the usage of ColorBrewer. We desire to select a color scheme for a two-dimensional bar chart for our sample data set of sales over a four-month period that we used extensively in Chapter 4. We have data from three regions to depict, so our “*Number of data classes*” is 3. Since we do not have an ordered data set or a data set with given break points, we select “*qualitative*” for the “*Nature of your data*” option. We select the “*colorblind safe*” option under the “*Only Show*” menu and deselect the “*borders option*” under the “*Context*” menu. We chose the “*3-class Set 2*” color scheme or the third and last color scheme counting from the left. Figure 6.20 shows our color scheme selection process.

This chosen color scheme is not considered to be “*photocopy friendly*”. We accept this limitation for our online infographic design. The specific ColorBrewer 2.0 URL to the qualitative color scheme we selected is noted as: <http://colorbrewer2.org/?type=qualitative&scheme=Set2&n=3>.

This URL shows our color scheme with the borders option selected. Now that we can export the URL or the various color hex code, RGB, or CMYK values, we can apply our

ColorBrewer 2.0: Qualitative color scheme

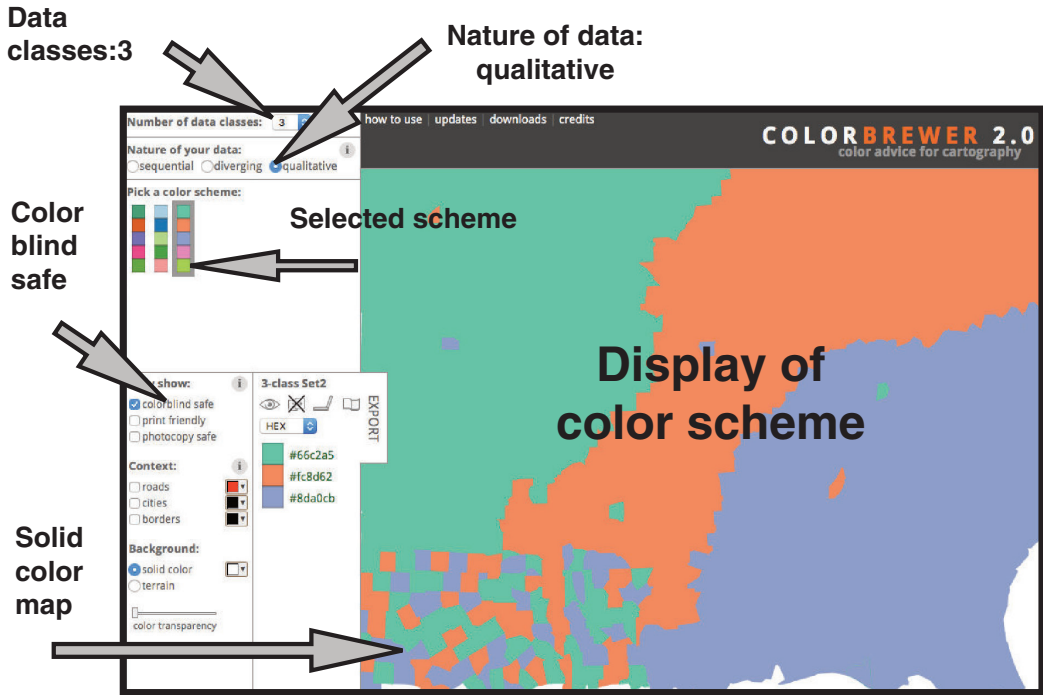


FIGURE 6.20 Selecting a color-blind safe qualitative color scheme using ColorBrewer 2.0. Image created by Theresa-Marie Rhyne, 2024, with the ColorBrewer 2.0 tool (<http://colorbrewer2.org>).

ColorBrewer 2.0 qualitative color scheme to our two-dimensional bar chart. We show these results in Figure 6.21.

6.7.2 Addressing Photocopy Safe and Printer Friendly Options

If we want to insure our ColorBrewer color scheme is “*printer friendly*” and “*photocopy safe*”, we select these two options with the “*colorblind safe*” option under the “*Only Show*” menu [16]. These three options cancel out all the “*qualitative*” color schemes under the “*Nature of your data*” menu. To address this situation, we select the “*sequential*” option under the “*Nature of your data*” menu to search for a workable color scheme. Since we do not have data with a break point, we do not select the “*diverging*” option at this time. We select a Yellow, Green, and Blue (YlGnBu) color palette as a possible option that addresses all three of our “*colorblind safe*”, “*printer friendly*”, and “*photocopy safe*” criteria. The specific ColorBrewer 2.0 URL to the color scheme we selected is noted as <http://colorbrewer2.org/?type=sequential&scheme=YlGnBu&n=3>.

Figure 6.22 shows the results of applying the sequential Yellow, Green, and Blue (YlGnBU) color scheme from ColorBrewer 2.0 to our two-dimensional bar chart example to produce the “*colorblind safe*”, “*printer friendly*”, and “*photocopy safe*” result.

Applying a ColorBrewer qualitative color scheme to a 2D bar chart

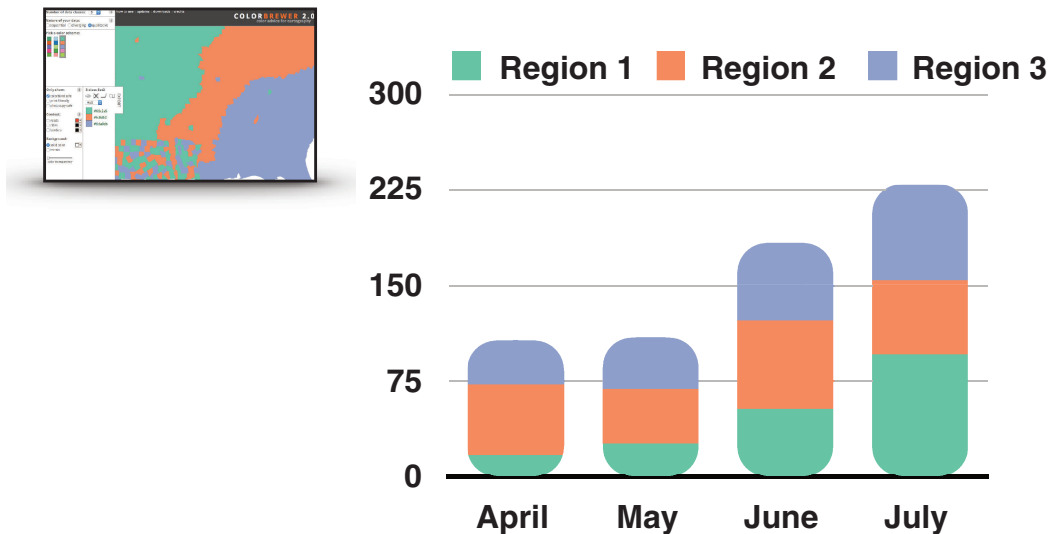


FIGURE 6.21 Applying the “3-class Set2” qualitative color scheme from ColorBrewer 2.0 to a 2D bar chart. Image created by Theresa-Marie Rhyne, 2024, using the ColorBrewer 2.0 tool, <http://colorbrewer2.org>.

6.7.3 Using ColorBrewer 2.0 with Only Two Variables

An item worth noting here is that if you have only two variables to plot or represent, it is still possible to use ColorBrewer by selecting a diverging color scheme. For a two-variable situation, set the “*Number of data classes*” equal to 3. Next, select the “*diverging*” button under the “*Nature of your data*”. The first six palettes under the “*diverging*” scheme option represent two colors separated by White. If we select only two color hues and eliminate the neutral White color, we have a color scheme for a two-variable plot. For our example, we return to our sales data set and plot data for two regions as a 2D stacked area chart. Under *diverging* color schemes in ColorBrewer 2.0, we select the first option on the left entitled “3-class BrBG” with the specific URL of <http://colorbrewer2.org/?type=diverging&scheme=BrBG&n=3>.

Our color scheme becomes the two colors of Brown and Blue-Green that we apply to our stacked area chart. We show these results in Figure 6.23.

6.8 HCL WIZARD

HCL Wizard is a perceptually uniform color selection system based on the HCL color space covered in Section 3.10. A color space is perceptually uniform if a change of length in any direction of the color space is perceived by a human as the same change. A non-uniform perceptual color map can have stark contrasts when transitioning from one hue to another hue. Figure 3.21 from Chapter 3 shows these differences between RGB and HCL

Applying a ColorBrewer sequential color scheme to a 2D bar chart

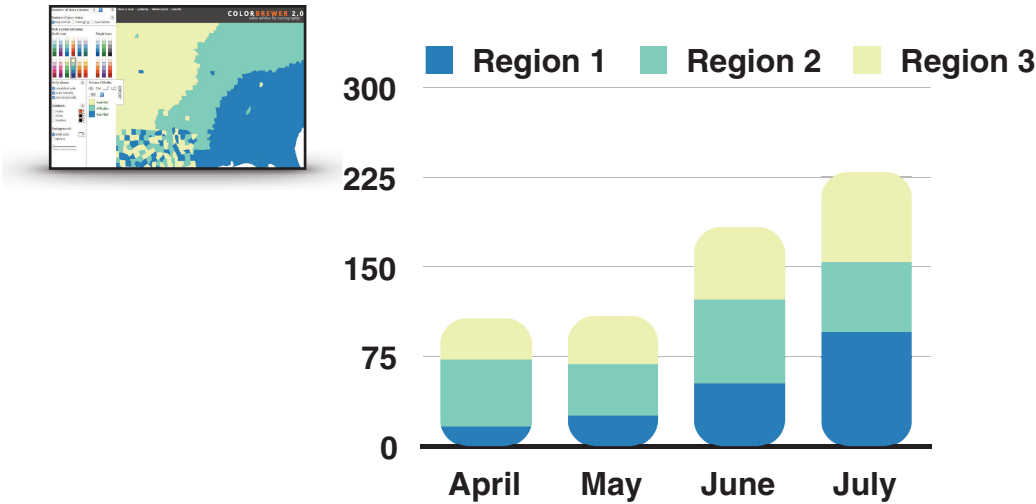


FIGURE 6.22 Applying the Yellow, Green, and Blue (YlGnBu) sequential color scheme from ColorBrewer 2.0 to a two-dimensional bar chart. Image created by Theresa-Marie Rhyne, 2024, with the ColorBrewer 2.0 tool, <http://colorbrewer2.org>.

Using ColorBrewer for a 2-variable chart

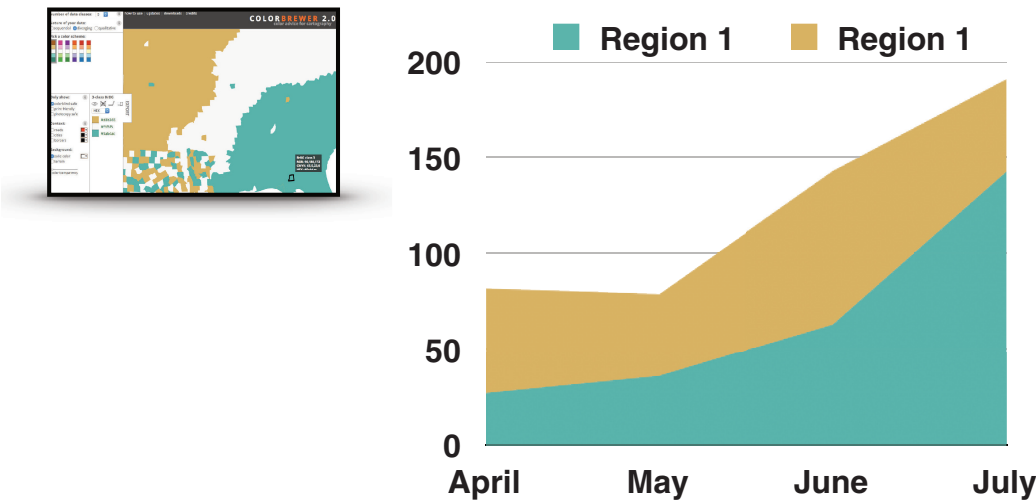


FIGURE 6.23 Applying a 3 data class diverging color scheme in ColorBrewer 2.0 to an infographic plate with two colors. Image created by Theresa-Marie Rhyne, 2024, with the ColorBrewer 2.0 tool, <http://colorbrewer2.org>.

HCL wizard user interface

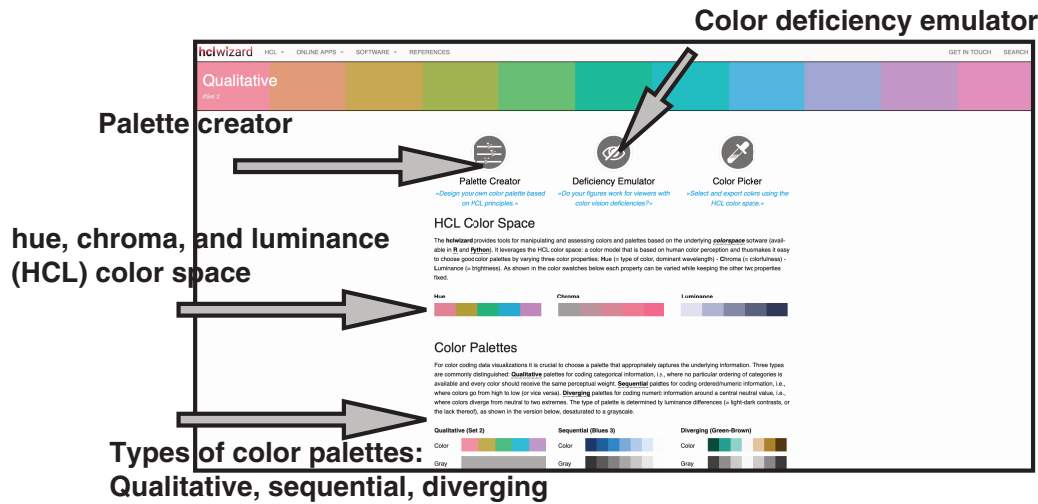


FIGURE 6.24 HCL Wizard website user interface (<https://hclwizard.org>). Image created by Theresa-Marie Rhyne, 2024, with the HCL Wizard tool.

color spaces. The HCL Wizard website, <https://hclwizard.org>, is based on the efforts of statisticians Ross Ihaka, Paul Murrell, Kurt Homik, Jason C. Fisher, Reto Stauffer, Claus O. Wilke, Claire D. McWhite, and Achim Zeileis, who are experts in the R software language for statistical computing and graphics. The team developed a tool called “*colorspace*” to address rainbow and non-perceptual uniform color map concerns noted in Section 2.11 of Chapter 2 [17]. The HCL Wizard website includes three major tools: *Palette Creator*, *Deficiency Emulator*, and *Color Picker* [18]. The color palettes are categorized according to the qualitative, sequential, and diverging concepts discussed in Section 5.2 of Chapter 5. The suite of tools also addresses protanopia (Red cone), deuteranopia (Green cone), tritanopia (Blue cone), and other color deficiencies. The user interface to the HCL Wizard website is shown in Figure 6.24.

6.8.1 Exploring the HCL Wizard Palette Creator Tool

Clicking on the *Palette Creator* icon yields a color scheme selection system with *Base Options* that include *Type of palette*, *Base color scheme*, and *Example*. There are also *Control Options* that include *Vision* parameters to address color deficiencies. The *Palette Creator* interface is similar to the ColorBrewer tool discussed previously in Section 6.7 and defaults to a *Map Example* and the *Basic: sequential (multi-hue) Purple-Blue color scheme*. Figure 6.25 shows HCL Wizard’s *Palette Creator* default user interface.

HCL wizard palette creator default interface

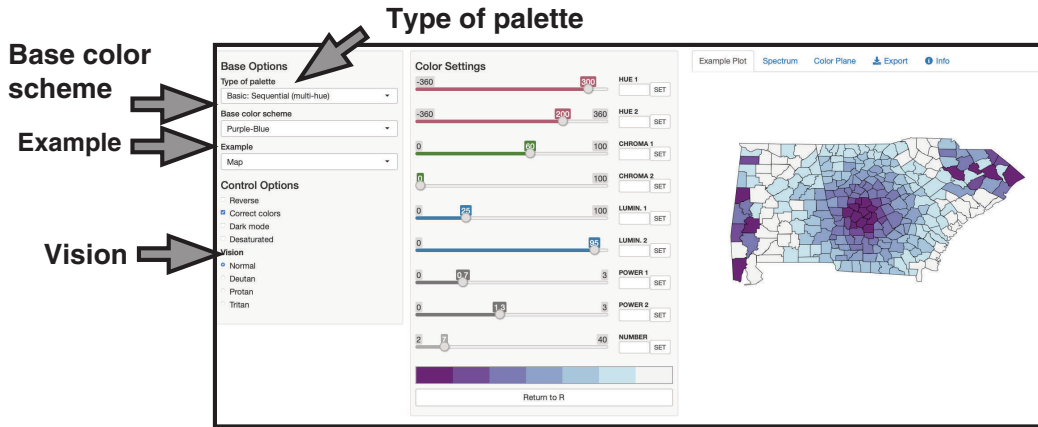


FIGURE 6.25 Default Map Example and the Basic: sequential (multi-hue) Purple-Blue color scheme interface of the HCL Wizard Palette Creator tool. Image created by Theresa-Marie Rhyne, 2024, with the HCL Wizard tool, (<https://hclwizard.org>).

Palette creator bar chart example

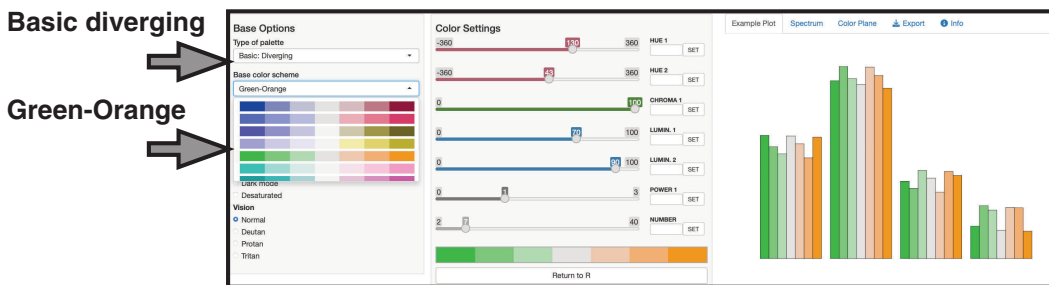


FIGURE 6.26 Creating a Green-Orange diverging color scheme with the bar chart example in the HCL Wizard Palette Creator tool. Image created by Theresa-Marie Rhyne, 2024, with the HCL Wizard tool, (<https://hclwizard.org>).

6.8.2 Creating an Example with the HCL Wizard Palette Creator

Let's work with the HCL Wizard *Palette Creator Bar Chart Example* to explore a diverging data color scheme the tool provides. Once *Diverging* is selected as the *Type of Palette*, the next option is to select a *Base Color Scheme*. Let's choose the *Green-Orange* option. The Palette Creator defaults to a *Correct* option but provides *Dark Mode* and *Desaturated* choices that can be explored at another time. Figure 6.26 shows these results with the HCL Wizard's *Palette Creator*.

Palette creator color deficiency tests for Green-Orange diverging scheme

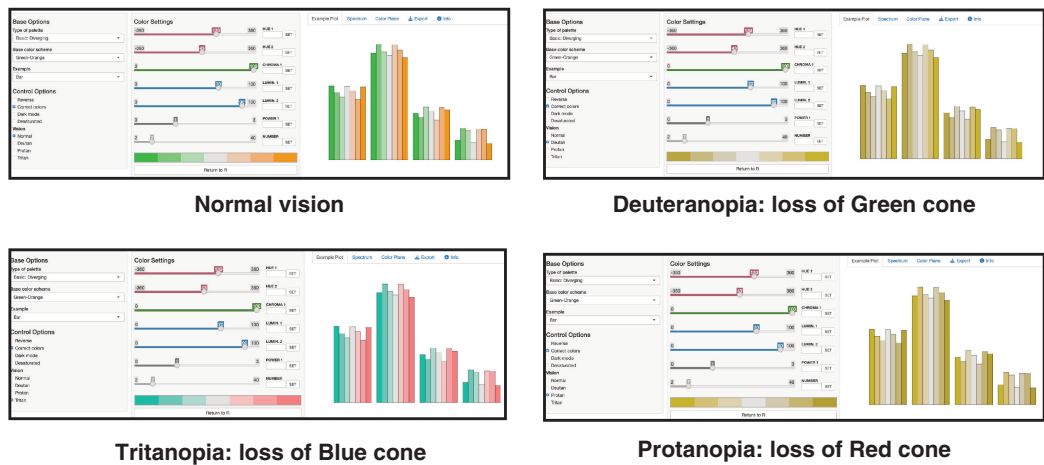


FIGURE 6.27 Checking protanopia, deuteranopia, and tritanopia color deficiency simulations for the Green-Orange diverging color scheme using the HCL Wizard Palette Creator tool, (<https://hclwizard.org>). Unfortunately, individuals with protanopia and deuteranopia are unable to distinguish between Green and Orange color elements. Image created by Theresa-Marie Rhyne, 2024, with the HCL Wizard tool.

We can use the HCL Wizard tools for exploring color deficiencies. In Figure 6.27, we show the results for protanopia (Red cone), deuteranopia (Green cone), and tritanopia (Blue cone) deficiencies. After examining the deuteranopia and protanopia simulations, it becomes evident that individuals with these color deficiencies might have difficulty distinguishing between the Orange and Green elements in the *Bar Chart Example*. As a result, another diverging color scheme might be desirable for addressing these factors.

We select the Magenta-Green *Advanced Diverging* color scheme as a possibility. Please note the *Palette Creator* tool defines this *Base color scheme* to be *Red-Green*. These results are shown in Figure 6.28.

The results of the *Vision* simulations are much more promising for this diverging color scheme. Individuals with protanopia, deuteranopia, and tritanopia will not view the exact color scheme but can distinguish between color elements. These results are shown in Figure 6.29.

The next step is to determine the specific numeric codes for the Magenta-Green diverging color scheme. Here, we consider a five-step data class. These specific codes are needed to apply these colors to an actual data visualization. The HCL Wizard Palette Creator provides an “*Export*” function with *HCL*, *RGB*, and *color hex* codes for this purpose. These specifics are shown in Figure 6.30. The HCL Wizard *Palette Creator* tool has assisted with a diverging color scheme suggestion that passes color deficiency tests.

Modified palette creator bar chart example

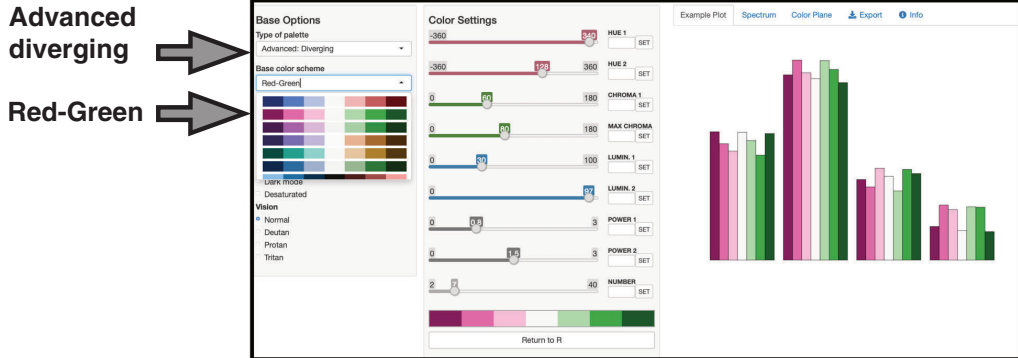


FIGURE 6.28 Selecting the Red-Green (actually Magenta – Green) advanced diverging color scheme with the bar chart example in the HCL Wizard Palette Creator tool. Image created by Theresa-Marie Rhyne, 2024, with the HCL Wizard tool, (<https://hclwizard.org>).

Palette creator color deficiency tests for Magenta-Green diverging scheme

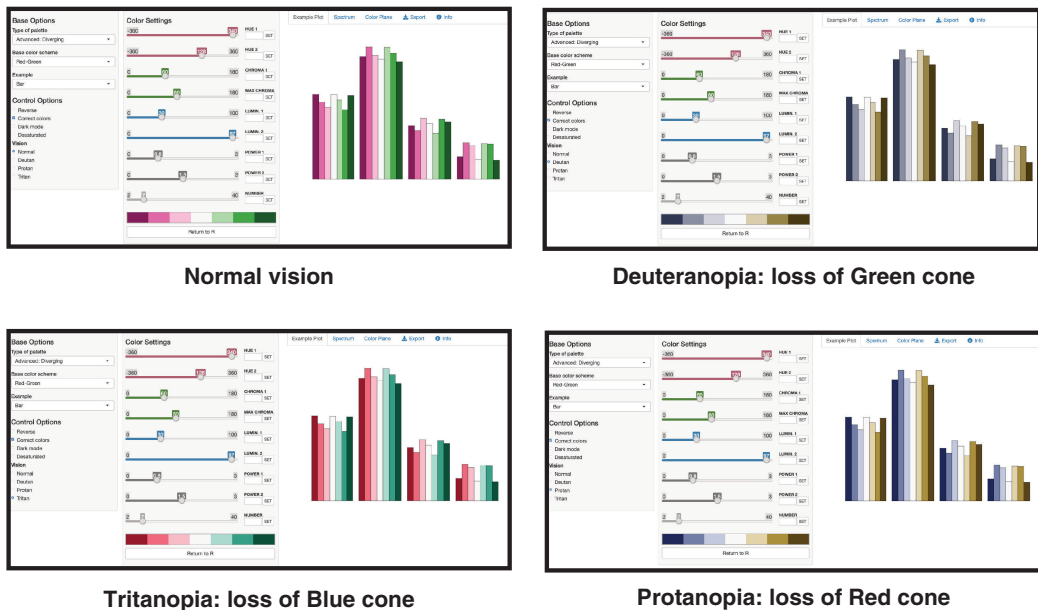


FIGURE 6.29 Checking protanopia, deuteranopia, and tritanopia color deficiency simulations for the Magenta-Green advanced diverging color scheme using the HCL Wizard Palette Creator tool. Note: the Palette Creator defines this scheme as Red-Green. This color scheme passes these tests since individuals with color deficiencies can distinguish between color elements. Image created by Theresa-Marie Rhyne, 2024, with the HCL Wizard tool, (<https://hclwizard.org>).

Exporting the numeric codes for a 5-step Magenta-Green diverging scheme

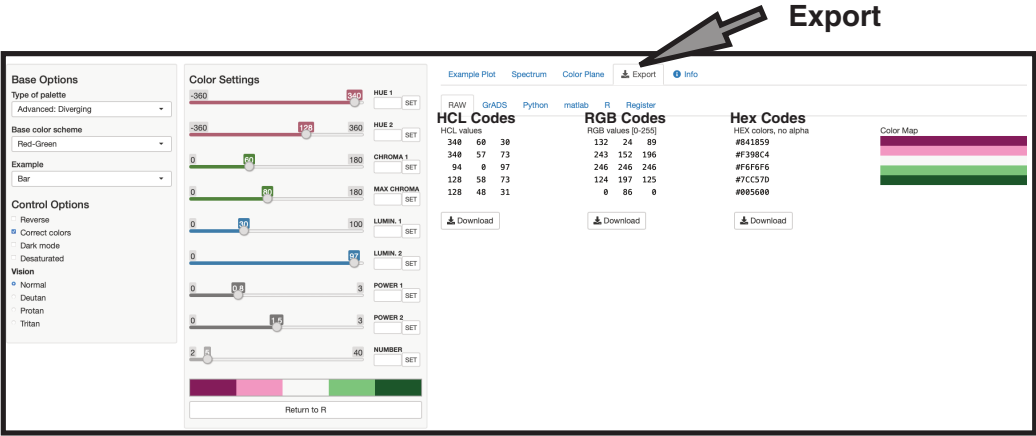


FIGURE 6.30 Using the “Export” function in HCL Wizard to determine the specific HCL, RGB, and color hex codes of a 5-step Magenta-Green diverging color scheme. Image created by Theresa-Marie Rhyne, 2024, with the HCL Wizard tool, (<https://hclwizard.org>).

6.9 DATA COLOR PICKER

Data Color Picker (<https://www.learnui.design/tools/data-color-picker.html#palette>) is a freely available color palette generator for quickly creating a qualitative, single-hue sequential or diverging color scheme like the concepts presented in Section 5.2 of Chapter 5. It is included as part of a “Learn UI Design” online video course developed by Erik Kennedy [19]. Color palettes are automatically created after entering specific color hex codes. A pie chart and basic map are provided to obtain context for the generated color schemes. Figure 6.31 shows the default qualitative or “palette” color scheme user interface [20].

6.9.1 Creating a Single-Hue Sequential Color Scheme with Data Color Picker

Here, we show how to create a single-hue sequential color scheme with Data Color Picker. In Section 6.5.3, during our discussion on the Paletton Color Scheme Designer, we noted a Purple color with the color hex code of #7608AA as part of a square color harmony. Let’s use this hue as the basis to build the sequence. Note that color hex codes are not case-sensitive, so #7608AA or #7608aa are the same hue. If we select the *SINGLE HUE* option from the top menu bar of Data Color Picker, we can enter the Purple color hex code as the first color on the left. This process quickly builds a single-hue sequential color scheme. We show these results in Figure 6.32.

6.9.2 Creating a Diverging Color Scheme with Data Color Picker

With a similar methodology, Data Color Picker supports building a diverging color scheme. Previously, in Section 3.12.3 of Chapter 3, we showed how the Pantone Connect app

Data color picker default interface

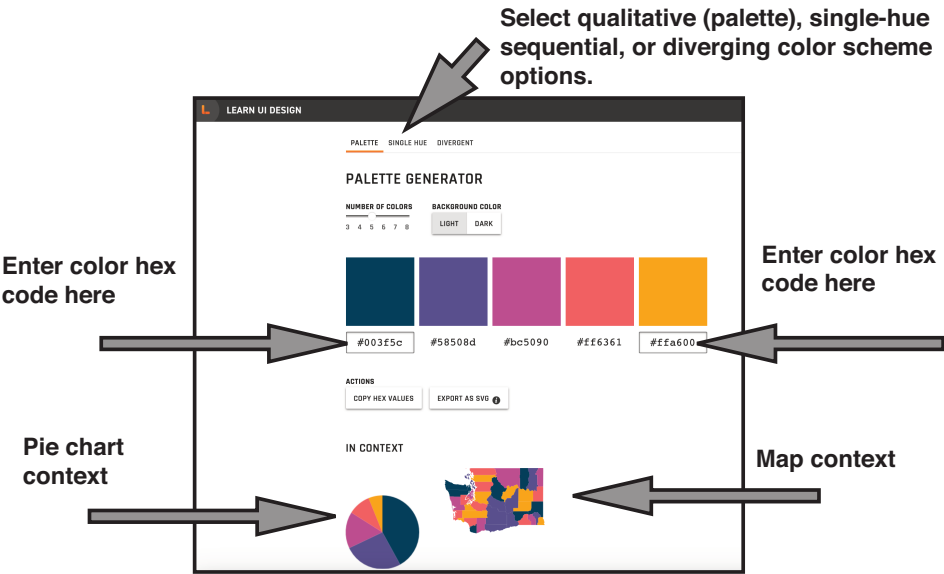


FIGURE 6.31 Default qualitative color palette and interface to Data Color Picker. Image created by Theresa-Marie Rhyne, 2024, with the Data Color Picker tool, <https://www.learnui.design/tools/data-color-picker.html#palette>.

Creating a single-hue sequence with data color picker

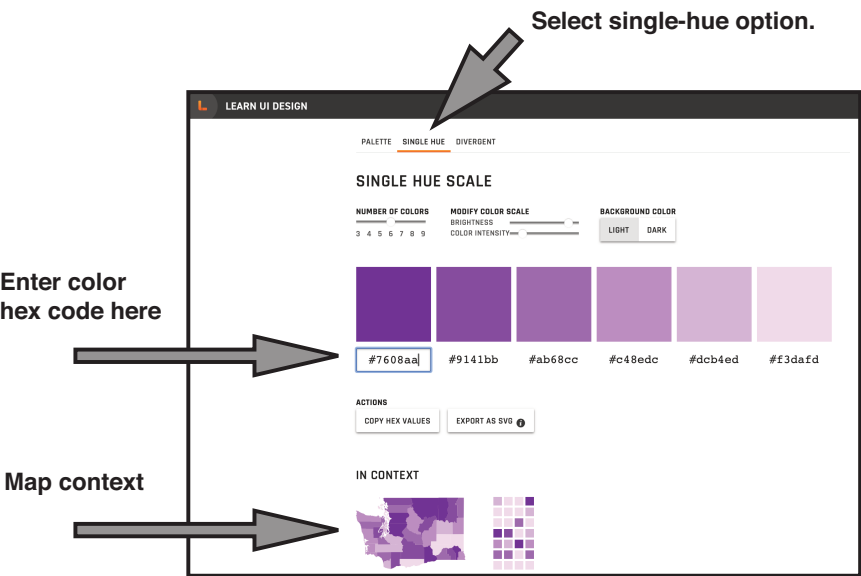


FIGURE 6.32 Creating a single-hue sequential color scheme with Data Color Picker. Image created by Theresa-Marie Rhyne, 2024, with the Data Color Picker tool, <https://www.learnui.design/tools/data-color-picker.html#palette>.

Creating a Diverging Color Scheme with Data Color Picker

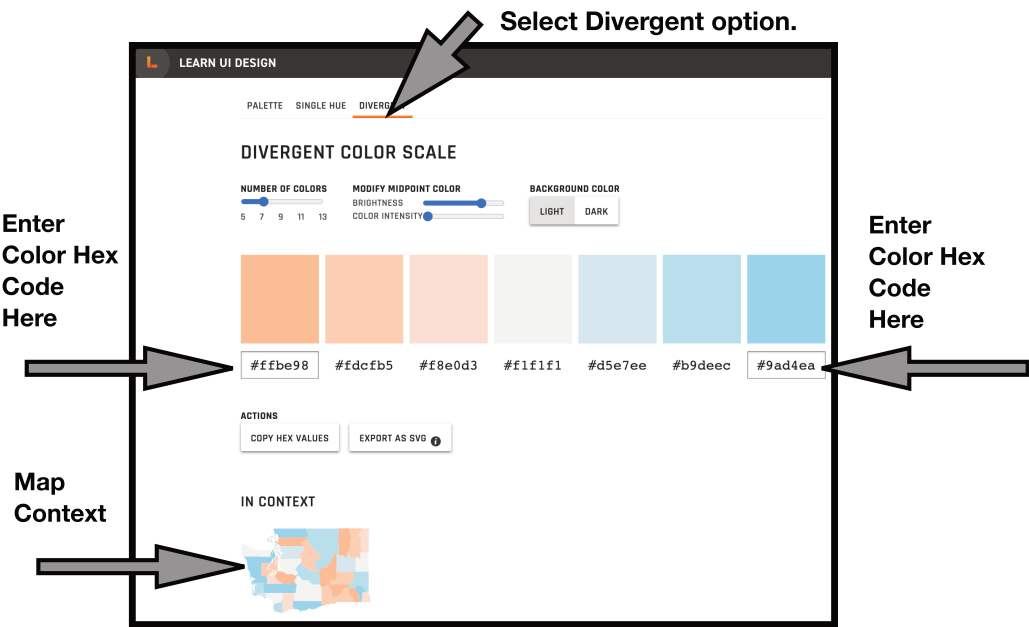


FIGURE 6.33 Building a diverging color scheme with Data Color Picker. Image created by Theresa-Marie Rhyne, 2024, with the Data Color Picker tool, <https://www.learnui.design/tools/data-color-picker.html#palette>.

provided the color hex code of #FFBE98 or #ffbe98 for Pantone’s Peach Fuzz hue. Pantone Connect also indicated that the complement to Peach Fuzz was the Atomizer hue with a color hex code of #9AD4EA or #9ad4ea. If we select the *DIVERGENT* option from the top menu bar of Data Color Picker, we can enter the Peach Fuzz color hex code as the first color on the left and the Atomizer color hex code as the last color on the right. Data Color Picker quickly assembles a diverging color scheme. We show these results in Figure 6.33.

6.10 CONCLUDING REMARKS

In this chapter, we have examined eight tools for analyzing and creating color palettes. These include (1) Adobe Color; (2) Adobe Capture; (3) the COLOURlovers community and its Color Palette Software (COPASO) tool; (4) Paletton’s Color Scheme Designer; (5) Viz Palette; (6) ColorBrewer 2.0; (7) HCL Wizard; and (8) Data Color Picker. We discussed key features of each tool and showed how each respective tool can be used to analyze or create a color palette. Each tool has its own approach for aiding in creating and assessing color schemes. As you continue on in your color studies, you will likely find additional color applications that work as part of your own digital color toolbox. At the end of this chapter, we provide references for further reading and online access to details about the color tools we have discussed in this chapter. In the next chapter, Chapter 7, we will discuss how some of these tools were used to address specific color palette requirements for selected case study examples.

REFERENCES

1. Adobe Inc. (2024), “Adobe Color”, <https://color.adobe.com>, accessed March 22, 2024.
2. Dam, P. (2023), “How to Utilize the Adobe Color Wheel”, 42 WEST, Adorama, posted August 4, 2023, <https://www.adorama.com/alc/adobe-color-wheel/>, accessed March 22, 2023.
3. Adobe Inc. (2024), “Adobe Capture”, <https://www.adobe.com/products/capture.html>, accessed March 26, 2024.
4. Cavazzana, L. (2023), “How to Use Adobe Capture to Transform Your Mobile Images”, Shotkit, <https://shotkit.com/adobe-capture/>, accessed March 26, 2024.
5. Adobe Inc. (2024), “What Are Creative Cloud Libraries?”, Creative Cloud Libraries, https://helpx.adobe.com/creative-cloud/help/libraries.html#library_use_cases, accessed March 26, 2024.
6. Monsef IV, D.A. (2011), *Color Inspirations: More than 3,000 Innovative Palettes from the Colourlovers.com Community*, Cincinnati, OH: HOW Books.
7. COLOURlovers.com (2024), <https://www.colourlovers.com/>, accessed March 26, 2024.
8. Paletton.com (2016), “Color Scheme Designer”, <https://paletton.com>, accessed March 28, 2024.
9. Velarde, O. (2022), “Using Paletton to Help Choose Your WordPress Website’s Color Palette”, elegant themes, <https://www.elegantthemes.com/blog/design/using-paletton-to-help-choose-your-wordpress-websites-color-palette>, accessed March 28, 2024.
10. Meeks, E. (2018), “Viz Palette for Data Visualization Color”, Medium, https://medium.com/@Elijah_Meeks/viz-palette-for-data-visualization-color-8e678d996077, accessed March 30, 2024.
11. Meeks, E. and Lu, S. (2018), “Viz Palette”, <https://projects.susielu.com/viz-palette>, accessed March 30, 2024.
12. Harrower, M.A. and Brewer, C.A. (2003), “ColorBrewer.org” An online tool for selecting color schemes for maps. *The Cartographic Journal*, 40 (1), 27–37.
13. Brewer, C.A. and Harrower, M. (2024), “The Pennsylvania State University and Axis Maps, ColorBrewer 2.0: Color Advice for Cartography”, <https://colorbrewer2.org/>, accessed March 30, 2024.
14. Brewer, C.A. (2015), *Designing Better Maps: A Guide for GIS Users*, 2nd ed., Redlands, CA: ESRI Press.
15. Krzywinski, M. (2024), “Brewer Palettes”, <https://mkweb.bcgsc.ca/brewer/>, accessed March 30, 2024.
16. Brewer, C.A., Hatchard, G.W., and Harrower, M.A. (2003), ColorBrewer in Print: A catalog of color schemes for maps. *Cartography and Geographic Information Science*, 30 (1), 5–32.
17. Stauffer, R., Mayr, G.J., Dabernig, M., and Zeileis, A. (2015), Somewhere over the rainbow: How to make effective use of colors in meteorological visualizations. *Bulletin of the American Meteorological Society*, 96 (2), 203–216. <https://journals.ametsoc.org/view/journals/bams/96/2/bams-d-13-00155.1.xml>.
18. Ihaka, R., Murrell, P., Homik, K., Fisher, J.C., Stauffer, R., Wilke, C.O., McWhite, C.D., and Zeileis, A. (2020), “HCL Wizard Web Site”, <https://hclwizard.org>, accessed April 2, 2024.
19. Kennedy, E. (2024), “Learn UI Design: The Complete Online Video Course & Resource Library”, <https://www.learnui.design>, accessed April 6, 2024.
20. Kennedy, E. (2024), “Data Color Picker”, <https://www.learnui.design/tools/data-color-picker.html#palette>, accessed April 6, 2024.

Case Study Examples of Colorizing Data Visualizations

IN THIS CHAPTER, WE present my process of colorizing a data visualization. We highlight three examples that applied this process. We show how generative AI provided suggestions for improving the colorization of the process diagram. The specific projects discussed here use color theory to provide insight into a particular problem under study. The three case studies include (1) using color detection to identify fresh color schemes from everyday objects; (2) identifying patterns associated with correlation in biological data; and (3) exploring the impacts of climate change in terms of the development of a tropical storm animation.

7.1 MY PROCESS OF COLORIZING A DATA VISUALIZATION

In 2020, I had the opportunity to contribute to a research paper entitled “Ten simple rules to colorize biological data visualization” by Georges Hattab, myself, and Dominik Heider [1]. Participating in this collaboration helped me explore data colorization in multiple ways. This resulted in my defining a *process of colorizing a data visualization*. On February 5, 2021, I shared this methodology in *Nightingale*, the journal of the Data Visualization Society [2].

This five-stage process includes the following steps:

1. Establish data classes for visualization and key color for visualization;
2. Select color rule, color harmony per criteria of your data;
3. Build color scheme. A color suggestion tool might be helpful;
4. Check and revise due to color deficiency, contrasts, or any pre-existing conditions;
5. Apply color scheme to data visualization. Some modifications might result.

Figure 7.1 shows a Grayscale version of the ring diagram of this process. As noted in Section 5.5.3 of Chapter 5, qualitative color schemes with five steps have difficulty passing

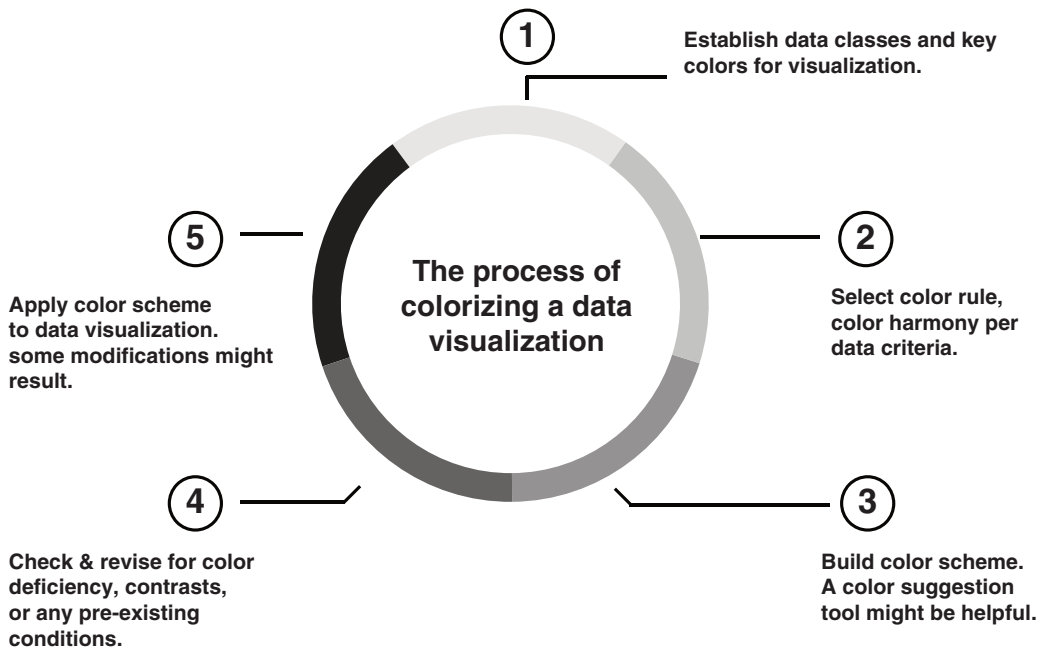


FIGURE 7.1 Grayscale version of the ring diagram for the “The Process of Colorizing a Data Visualization” with numbers and texts associated with each step. Image created by Theresa-Marie Rhyne, 2024.

color deficiency tests. As a result, we have prepared for the colorization of the ring diagram by providing numbers and texts associated with each step.

7.1.1 Asking ChatGPT for Qualitative Color Scheme Suggestions That Pass Color Deficiency

To colorize the five-step ring diagram, we asked the ChatGPT generative AI tool for qualitative data color scheme suggestions that pass color deficiency tests [3]. We introduced this generative AI tool in Section 3.11.4 of Chapter 3. Our query was phrased as “*specify by color hex codes qualitative color schemes that pass color deficiency tests*”. ChatGPT provided the following response:

Absolutely! Designing color schemes that are accessible to individuals with color vision deficiencies is essential. Here are some color schemes specified by hex codes that pass color deficiency tests, particularly the deuteranopia (green-blindness) and protanopia (red-blindness):

Color Scheme for Deuteranopia (Green-Blindness): #FFA07A (Light Salmon); #6495ED (Cornflower Blue); #CCCCFF (Periwinkle); #FFD700 (Gold); #808080 (Gray)

Color Scheme for Protanopia (Red-Blindness): #4682B4 (Steel Blue); #7FFF00 (Chartreuse); #FFFF99 (Light Yellow); #800080 (Purple); #A9A9A9 (Dark Gray)

These color combinations are chosen to maintain contrast and differentiation even for individuals with red-green color deficiencies. They ensure that the colors used in data visualization, or any design are distinguishable and easily interpreted by a wider audience. Adjusting the shades slightly within the same color family can also enhance accessibility without compromising the intended design.

We named the two suggested color schemes as *ChatGPTQualDeuter* and *ChatGPTQualProtan*.

7.1.2 Using Adobe Color to Examine the *ChatGPTQualDeuter* and *ChatGPTQualProtan* Suggestions

The next step was to use Adobe Color to visually map the ChatGPT five-step color schemes [4]. This was done by entering the color hex codes ChatGPT specified into the Adobe Color app to build each color scheme. It was also possible to use the Adobe Color’s color blindness options as checks for color deficiency. Figure 7.2 shows the results of these efforts. For a detailed discussion on the Adobe Color tool, see Section 6.2 of Chapter 6.

Adobe Color indicated that “No Conflicts found. Swatches are color blind safe” for both *ChatGPTQualDeuter* and *ChatGPTQualProtan*. Looking at the visual results, we determined that ChatGPT suggested two qualitative color palettes that were pleasing combinations while passing deuteranopia, protanopia, and tritanopia deficiency tests. Individuals with these color deficiencies can distinguish between the five color elements of each color scheme. Figure 7.3 shows *ChatGPTQualDeuter* and *ChatGPTQualProtan* applied to the ring diagram for the “The Process of Colorizing a Data Visualization”. My personal preference was for *ChatGPTQualDeuter*.

Using Adobe color to map the qualitative color schemes and check for color deficiencies of the ChatGPT specified color schemes.

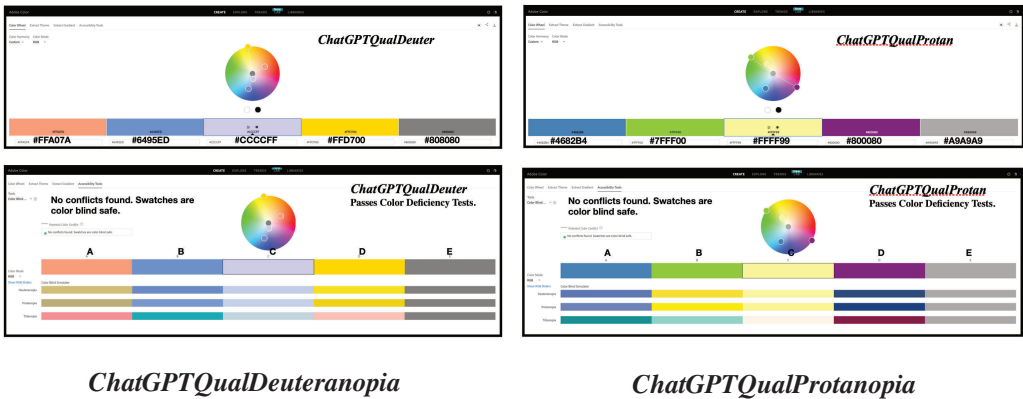


FIGURE 7.2 Using Adobe Color to visually map and check for color deficiencies of the ChatGPT-specified qualitative color schemes that are intended to address either deuteranopia or protanopia deficiencies. Composite image created by Theresa-Marie Rhyne, 2024, with the Adobe Color tool.

Applying ChatGPT_QualDeuteranopia & ChatGPT_QualProtanopia to my process of colorizing a data visualization diagram

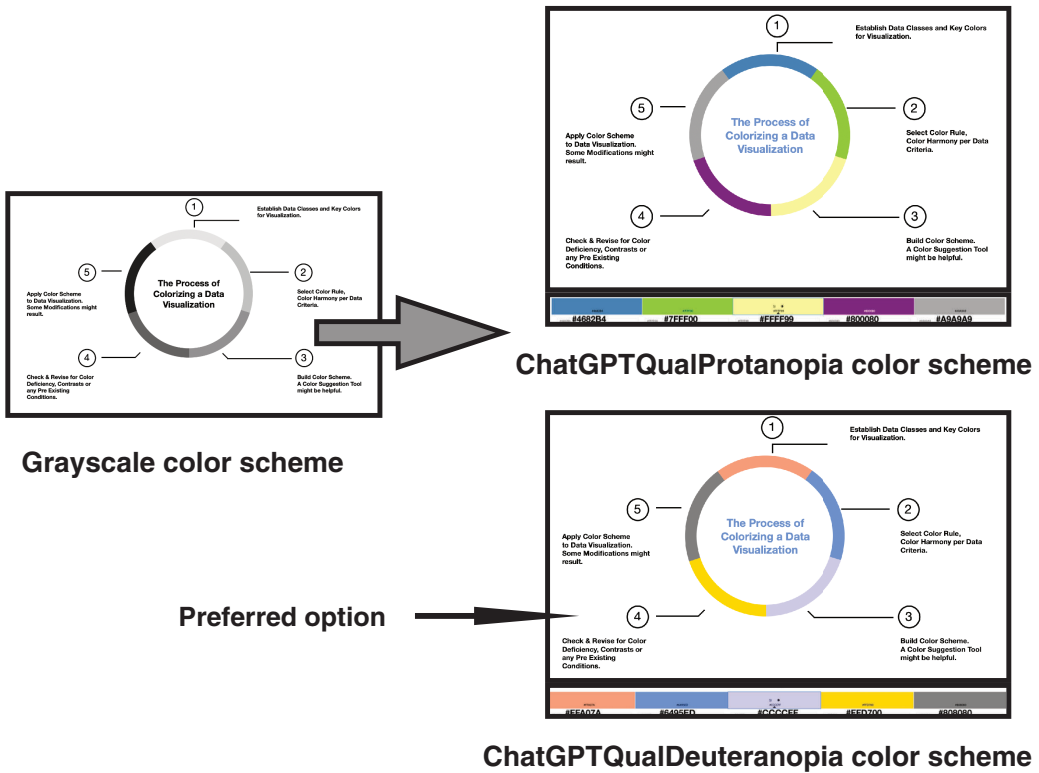


FIGURE 7.3 Applying the ChatGPTQualDeuter and ChatGPTQualProton qualitative color schemes to the ring diagram for the “The Process of Colorizing a Data Visualization”. The ChatGPTQualDeuter color scheme is the preferred option. Composite image created by Theresa-Marie Rhyne, 2024.

Notice that rather than specifying five distinct hues, the chatbot specified qualitative data color schemes composed of four colors with one neutral hue. This clever solution provided five-step qualitative color palettes with no implied magnitude differences while also addressing color deficiency issues. Figure 7.4 summarizes these efforts. In the next sections of this chapter, we will apply this colorization process to three case studies.

7.1.3 Review of Applying Generative AI (ChatGPT) to Coloring a Five-Element Data Set

In this case study, we defined a five-stage process for colorizing a data visualization. These five stages are as follows: (1) *establish data classes for visualization and key color for visualization*; (2) *select color rule, color harmony per criteria of your data*; (3) *build color scheme. A color suggestion tool might be helpful*; (4) *check and revise due to color deficiency, contrasts, or any pre-existing conditions*; and (5) *apply color scheme to data visualization. Some*

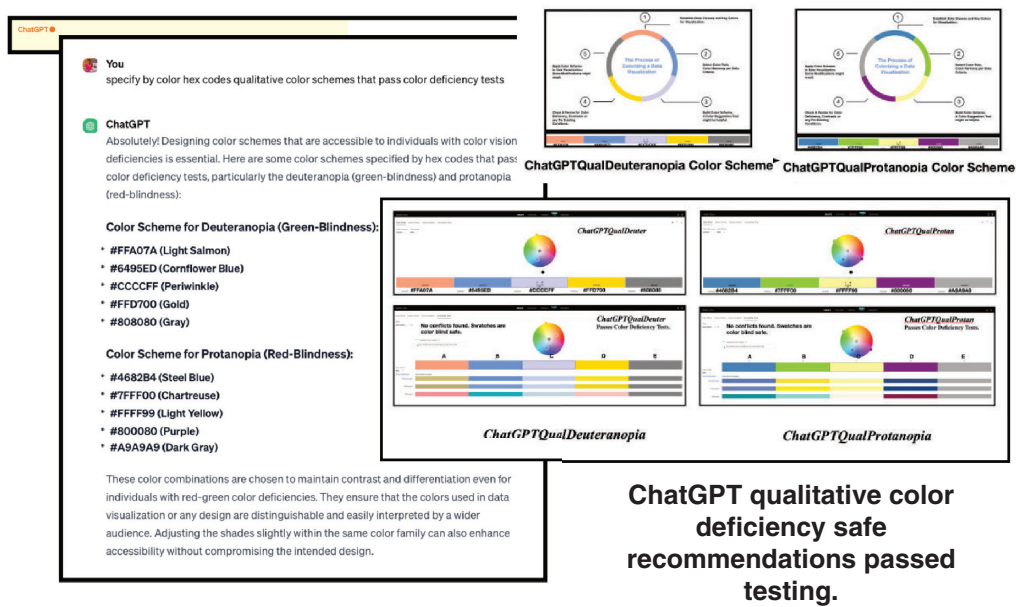


FIGURE 7.4 Visual summary of the effort to use ChatGPT to specify, by color hex codes, qualitative data color schemes that pass color deficiency tests. Composite image created by Theresa-Marie Rhyne, 2024.

modifications might result. Next, we used ChatGPT to specify, by color hex codes, color elements that passed color deficiency tests for this five-stage process. The chatbot specified qualitative data color schemes composed of four colors with one neutral hue. This clever solution provided five-step qualitative color palettes with no implied magnitude differences while also addressing color deficiency issues.

7.2 USING COLOR DETECTION TO IDENTIFY FRESH COLOR SCHEMES FROM EVERYDAY OBJECTS

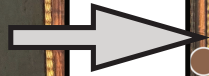
Everyday objects or perhaps your favorite set of colors can form the basis for colorizing your digital media or data visualizations. Here, we have used the Adobe Capture app to extract colors from a photograph of the “Vanitas Flower Still Life” painting. This painting was created by Willem van Aelst in the 1656–1657 time frame and is on display at the North Carolina Museum of Art [5]. Adobe Capture automatically selected five colors from the image for an initial color scheme [6]. For each color specified, a radio button or color sensor was generated. The Adobe Capture app is discussed in further detail in Section 6.3 of Chapter 6. Figure 7.5 depicts this color capture effort.

7.2.1 Being a Color Detective

We further explored the colors in the “Vanitas Flower Still Life” image by manually repositioning the five color sensors that Adobe Capture provided. This facilitated being a “color detective”, searching for color elements that might be of interest. Figure 7.6 shows the results of these efforts. The resulting color scheme was named Vanitas.



Original image from an iPhone camera roll.



Initial color scheme extracted by Adobe Capture app.

FIGURE 7.5 Using the Adobe Capture app to automatically extract five colors from an iPhone photo of the “Vanitas Flower Still Life” painting, created by Willem van Aelst in the 1656-to-1657 time frame and on display at the North Carolina Museum of Art. Composite image created by Theresa-Marie Rhyne, 2024.

7.2.2 Determining the Color Hex Codes or RGB Numbers

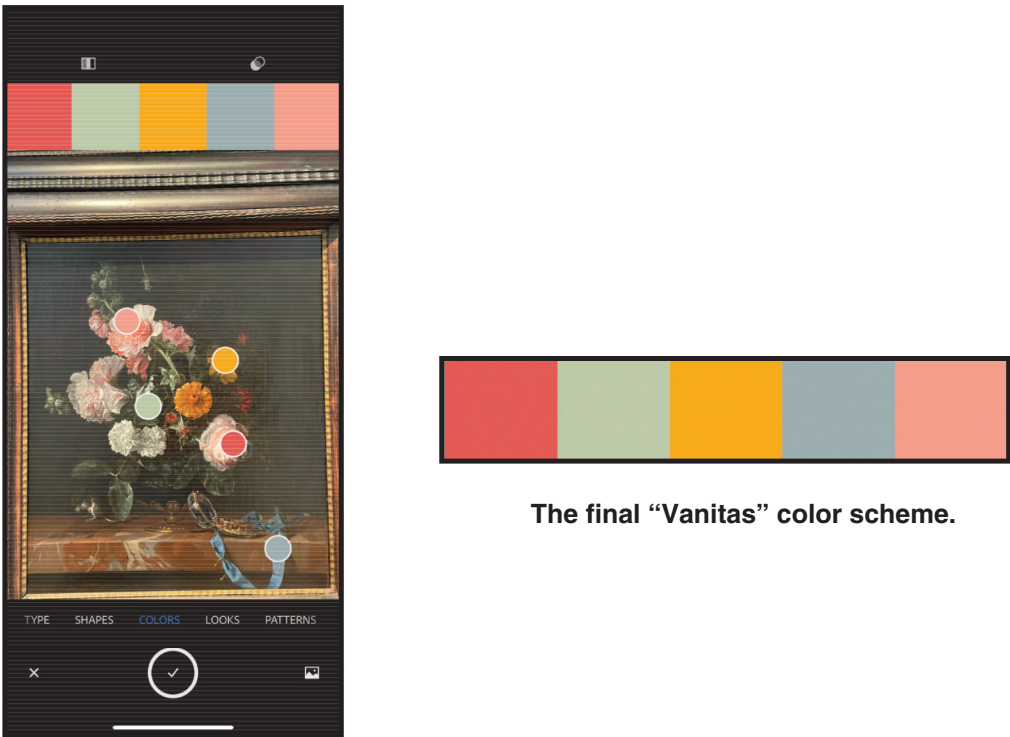
To finalize the *Vanitas* color scheme, we needed to establish the color hex codes or RGB numbers for each element of the color schemes. When hovering over each specific color swatch, Adobe Capture provided the color hex code and the RGB numbers. Figure 7.7 shows these results with a star added in each selected color swatch for illustration purposes.

7.2.3 Applying the Five-Stage Process of Colorizing a Data Visualization

Next, the *Vanitas* color scheme was applied to a data visualization according to the five-stage colorization process.

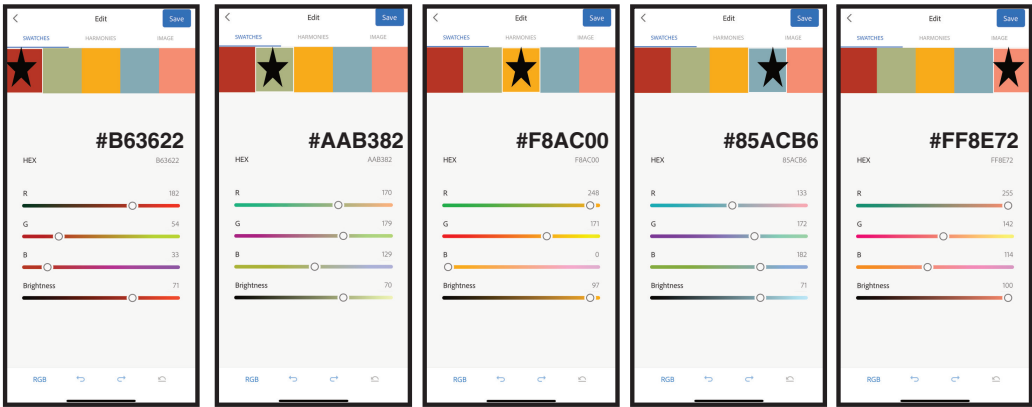
1. Establish Data Classes for Visualization and Key Color for Visualization:

For a basic example, we returned to the sales data of Chapter 4 and focused on three independent regions to depict in a single visualization. The key color was the Yellow #F8AC00 in the *Vanitas* color scheme.



Manual repositioning of Adobe Capture’s five color sensors.

FIGURE 7.6 Repositioning Adobe Capture sensors and exploring the colors in the “Vanitas” image to build a color scheme. Composite image created by Theresa-Marie Rhyne, 2024.



Adobe Capture provides the color hex codes and RGB numbers for each of the five elements of a color scheme.

FIGURE 7.7 Locating the color hex codes and RGB numbers for each color in the “Vanitas” scheme. In color hex codes, these are Red #B63622, Green #AAB382, Yellow #F8AC00, Blue #85ACB6, and Pink #FF8E72. Composite image created by Theresa-Marie Rhyne, 2024.

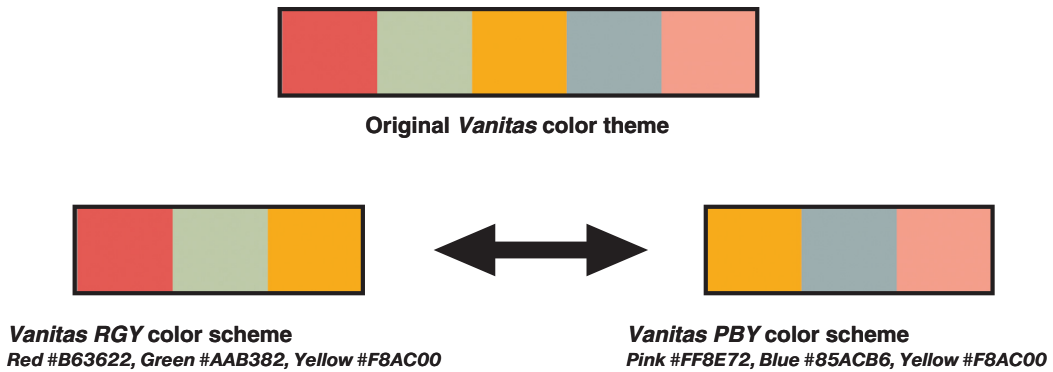


FIGURE 7.8 Establishing two color scheme options: *Vanitas RGY* – for Red #B63622, Green #AAB382, and Yellow #F8AC00; and *Vanitas PBY* – for Pink #FF8E72, Blue #85ACB6, and Yellow #F8AC00. Composite image created by Theresa-Marie Rhyne, 2024.

2. *Select Color Rule, Color Harmony per Criteria of your Data:*

Since only three colors were needed to define each distinct region, we created two color scheme options: *Vanitas RGY* – for Red #B63622, Green #AAB382, and Yellow #F8AC00; and *Vanitas PBY* – for Pink #FF8E72, Blue #85ACB6, and Yellow #F8AC00.

3. *Build Color Scheme. A Color Suggestion Tool Might Be Helpful:*

Figure 7.8 shows the *Vanitas RGY* and *Vanitas PBY* color schemes and how they were split off from the original *Vanitas* color scheme.

4. *Check & Revise due to Color Deficiency, Contrasts, or Any Pre-Existing Conditions:*

Here, we used the Viz Palette tool to explore various generic data visualizations and perform preliminary color deficiency checks [7]. The Viz Palette app is discussed in further detail in Section 6.6 of Chapter 6.

Figure 7.9 shows the results of entering the color hex codes for *Vanitas RGY* into Viz Palette and checking for protanopia and deuteranopia. Viz Palette also showed various chart types, including a bar chart, a tree map, a line plot, and an area chart. Although the original *Vanitas RGY* color scheme will not appear the same, the Viz Palette color deficiency checks indicate that individuals with protanopia or deuteranopia deficiencies can distinguish three different color elements.

Next, the *Vanitas PBY* color scheme was applied to Viz Palette for a similar examination. Viz Palette showed various data visualization options for the color scheme. *Vanitas PBY* also passed protanopia and deuteranopia color deficiency checks. Figure 7.10 shows these results.

5. *Apply Color Theme to Data Visualization. Some Modifications Might Result:*

After viewing the Viz Palette options for the two proposed color schemes, we decided to create an area chart to depict the sales data for three regions. It was difficult to decide a favorite one between the *Vanitas RGY* and the *Vanitas PBY* color schemes. Figure 7.11 shows these results.

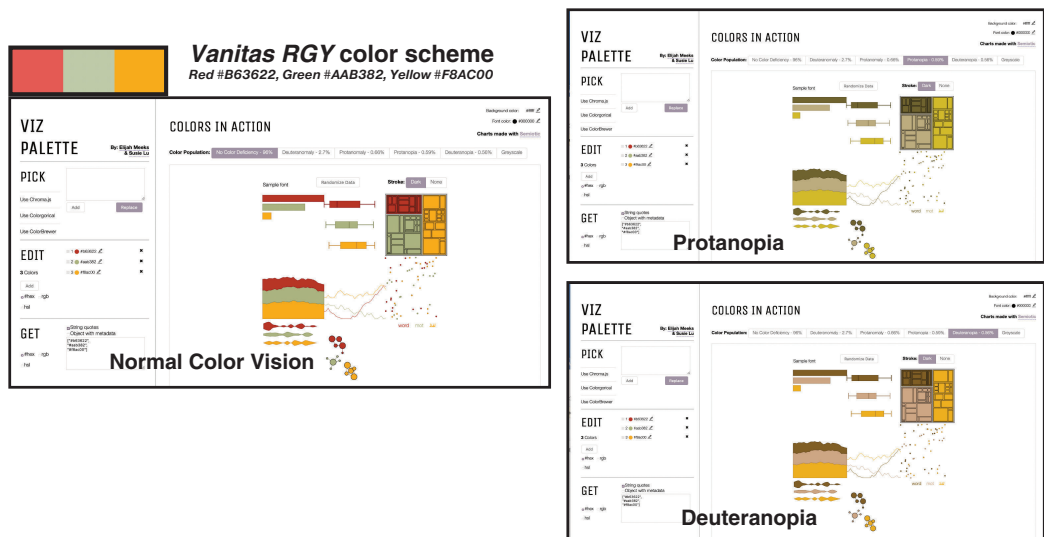


FIGURE 7.9 Using the Viz Palette app to explore generic data visualization options and perform protanopia and deuteranopia color deficiency checks for the Vanitas RGY color scheme. The color scheme passes these color deficiency checks. Composite image created by Theresa-Marie Rhyne, 2024.

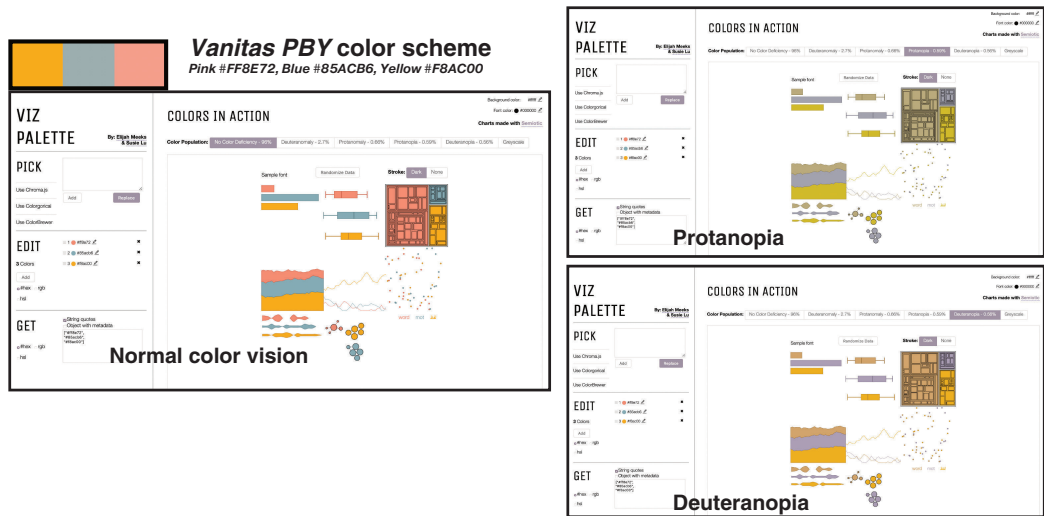
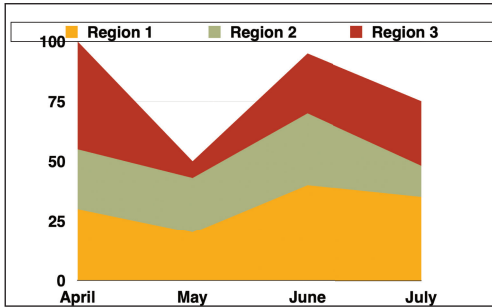


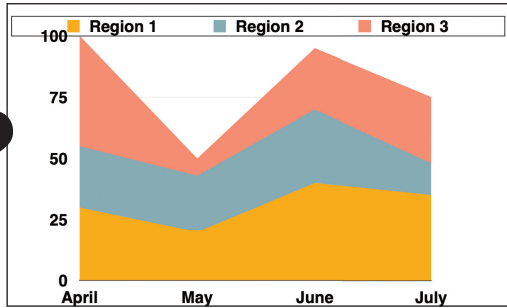
FIGURE 7.10 Using the Viz Palette app to explore generic data visualization options and perform protanopia and deuteranopia color deficiency checks for the Vanitas PBK color scheme. The color scheme passes these color deficiency checks. Composite image created by Theresa-Marie Rhyne, 2024.

To be sure of color deficiency, final checks of the area chart visualizations using the Color Blindness Simulator tool (Coblis) were performed [8]. We previously covered Coblis in Section 2.9 of Chapter 2. Coblis facilitated checking for the tritanopia (Blue cone) deficiency in addition to the protanopia (Red cone) deficiency and

Area Chart with the *Vanitas RGY* color scheme
Red #B63622, Green #AAB382, Yellow #F8AC00



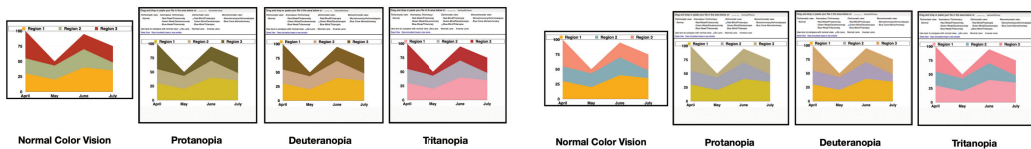
Area Chart with the *Vanitas PBY* color scheme
Pink #FF8E72, Blue #85ACB6, Yellow #F8AC00



?

FIGURE 7.11 Comparison of area chart visualizations using the *Vanitas RGY* and the *Vanitas PBY* color schemes. Composite image created by Theresa-Marie Rhyne, 2024.

Final color deficiency checks for *Vanitas RGY* and the *Vanitas PBY* area charts



Area chart with *Vanitas RGY* color scheme

Area chart with *Vanitas PBY* color scheme

FIGURE 7.12 Comparison of color deficiency checks for the *Vanitas RGY* and the *Vanitas PBY* area charts using the Color Blindness Simulator (Coblis), <https://www.color-blindness.com/coblis-color-blindness-simulator/>. Composite image created by Theresa-Marie Rhyne, 2024.

the deuteranopia (Green cone) deficiencies. The checks for the area chart with the *Vanitas RGY* color scheme indicated that individuals with color deficiencies can distinguish three distinct colors. Upon review of the *Vanitas PBY* color scheme checks, it appeared individuals with Blue cone deficiencies could be challenged to tell the difference between the original Pink and Yellow colors in the color scheme. The differences between *Vanitas PBY* colors for the protanopia or deuteranopia deficiencies were also very minor when applied to the actual area chart. These results are shown in Figure 7.12.

As a result of the Coblis deficiency analyses with the actual area chart visualization, the *Vanitas RGY* color scheme was selected as the final solution for this case study. Figure 7.13 shows a simplified flowchart of the final color scheme selection process.

Summary of the selection of the Vanitas RGY color scheme

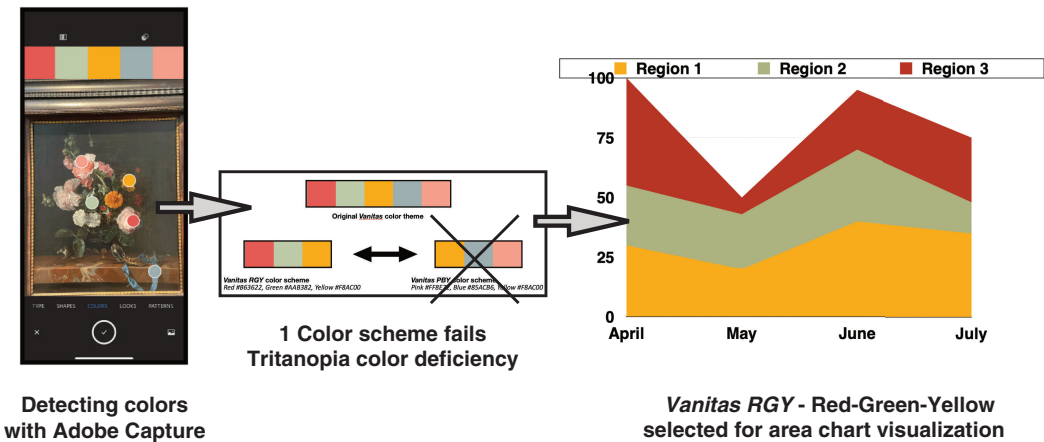


FIGURE 7.13 Simplified flowchart of the selection process of the Vanitas RGY color scheme for the area chart data visualization. Composite image created by Theresa-Marie Rhyne, 2024.

7.2.4 Review of Using Color Detection to Identify Fresh Color Schemes from Everyday Objects

In this case study, the Adobe Capture app was used to automatically extract five colors from an iPhone photo of the “Vanitas Flower Still Life” painting, created in the 1656-to-1657 time frame. The artwork is housed at the North Carolina Museum of Art. Two color schemes of three elements were developed to eventually be applied to a data visualization. The five-stage colorization for data visualization process was applied to the color scheme alternatives, and the Viz Palette tool was used to assess visualization alternatives. Both color scheme options passed the protanopia (Red cone) and the deuteranopia (Green cone) deficiency tests. However, only one alternative passed the tritanopia (Blue cone) deficiency and was selected for the final area chart visualization.

7.3 IDENTIFYING PATTERNS ASSOCIATED WITH CORRELATION IN BIOLOGICAL DATA

The process of detecting novel patterns of correlation in large-scale molecular biological data can aid in discovering the existence of previously unknown cellular regulatory mechanisms. Researchers have successfully applied the mathematical modeling of DNA microarray data to correctly predict previously unknown global modes of regulation for genes (for further reading on such efforts, see Reference [9]). In a project with the Scientific Computing and Imaging (SCI) Institute at the University of Utah [10], we applied color theory principles to aid in creating a visualization approach to support this type of research. Central to our biological visualization efforts was the recognition that our research scientists would be working in a Red, Green, and Blue (RGB) color display environment and could have color vision deficiencies. A key objective was to design a color scheme that would aid in detecting patterns for correlation

in the large-scale molecular biological data. The visible light spectrum and other color vision principles were discussed in Chapter 2 of this book.

7.3.1 Designing a Color Scheme Solution

Two approaches to building the final color scheme were developed: (1) building a complementary color harmony with Adobe Color [5] and (2) applying a diverging color scheme from the HCL Wizard system [13]. The final visualization results were a hybrid of both solutions. We step through this specific colorization effort using the five-stage process for colorizing a data visualization.

1. Establish Data Classes for Visualization and Key Color for Visualization:

The biological data was presented in mosaic patterns that needed to be colorized. Figure 7.14 shows an initial Grayscale diagram of a typical data set. It is like a heat-map, but it is not due to the unique positioning of Data Set #1 and #2. The chief scientist desired to have a visual contrast between Data Set #1 and Data Set #2 to detect patterns in the results of her computational model. This resulted in two classes of data with a potential neutral zone.

One of the team members had a Red-Green color deficiency. This immediately eliminated consideration for a Red-Green color scheme that would fail protanopia (Red cone) or deuteranopia (Green cone) color deficiency tests. The Blue-Yellow color scheme that would fail tritanopia (Blue cone) tests was also eliminated even though this color deficiency was not a problem with the specific team member [11]. Figure 7.15

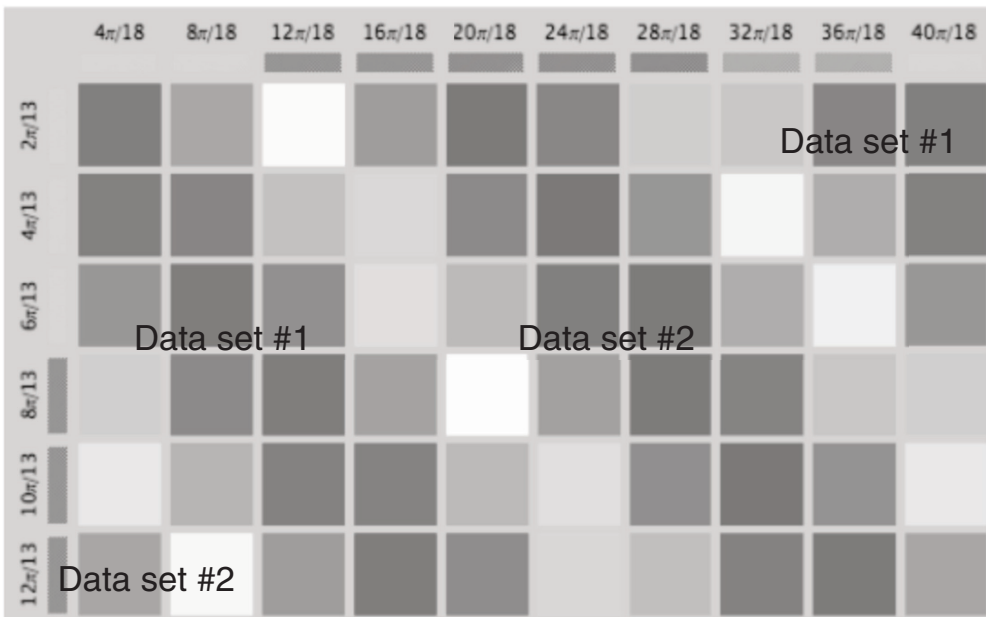


FIGURE 7.14 Initial Grayscale diagram of the visualization for modeling of DNA microarray data. Image created by Theresa-Marie Rhyne, 2024.

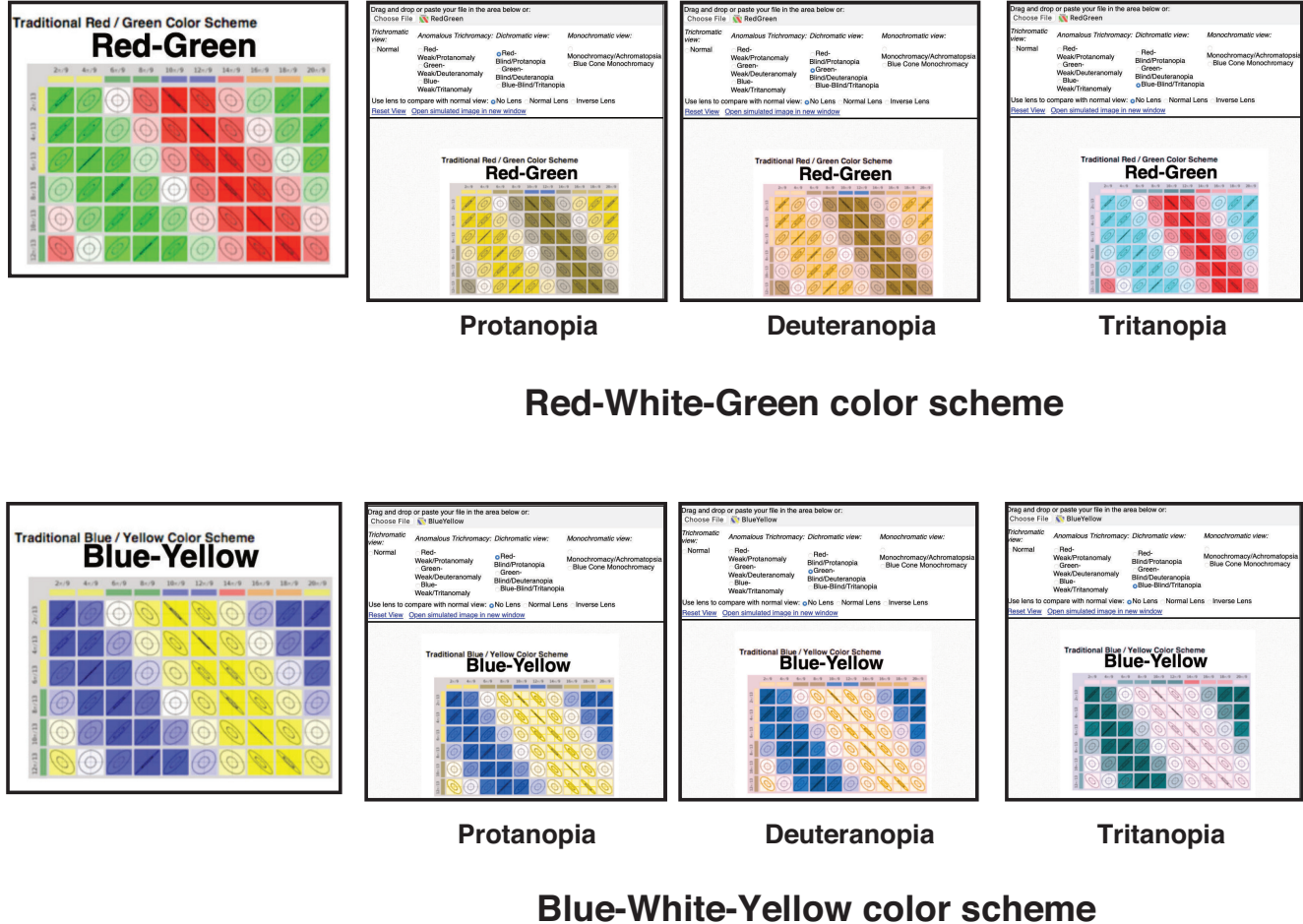


FIGURE 7.15 Color deficiency analyses for Red-Green and Blue-Yellow color schemes using the Color Blindness Simulator (Coblis) tool, <https://www.color-blindness.com/coblis-color-blindness-simulator/>. Composite image created by Theresa-Marie Rhyne, 2024.

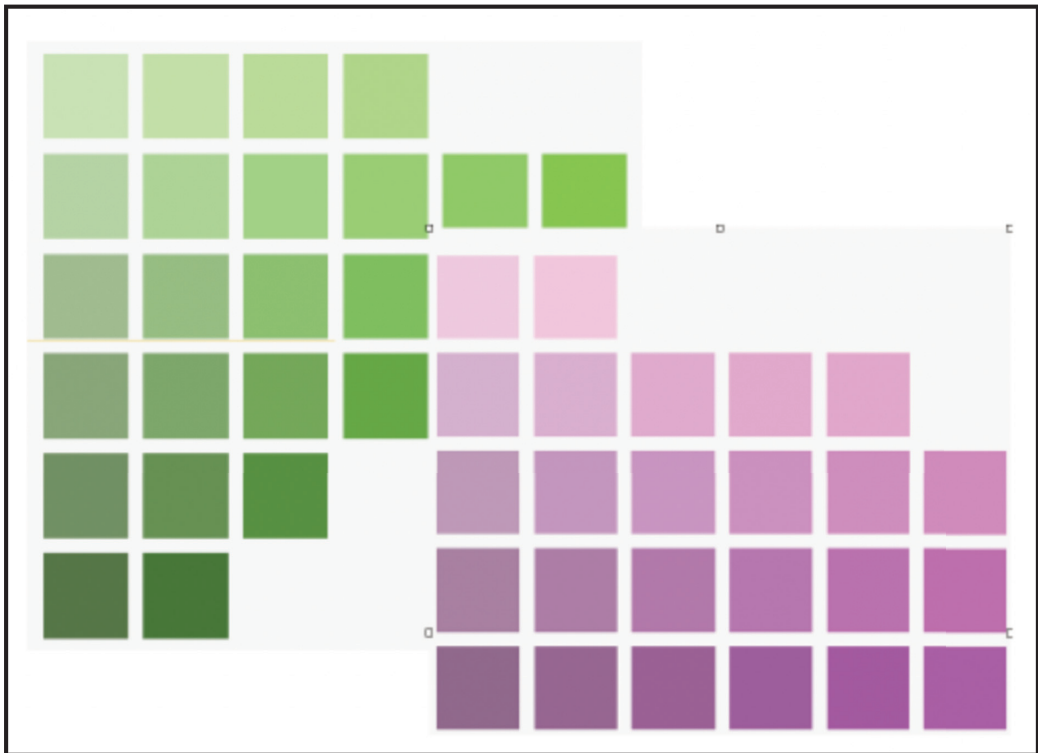
shows color deficiency analyses for Red-Green and Blue-Yellow color schemes using the Color Blindness Simulator (Coblis) tool [8]. The key colors Purple and Green were considered as potential contrasting colors.

2. *Select Color Rule, Color Harmony per Criteria of your Data:*

In building our initial color scheme concept, we recalled that the layout of the Munsell color cross sections had similarities to the mosaic patterns in the DNA microarray data visualizations. The two-dimensional cross sections of the Munsell 10 GY (Green-Yellow) and the Munsell 10 P (Purple) hues were used to build a preliminary mock-up for this colorization effort. These results are shown in Figure 7.16. Reference [12] provides additional details on the mock-up design. Section 3.8 of Chapter 3 describes the Munsell color system.

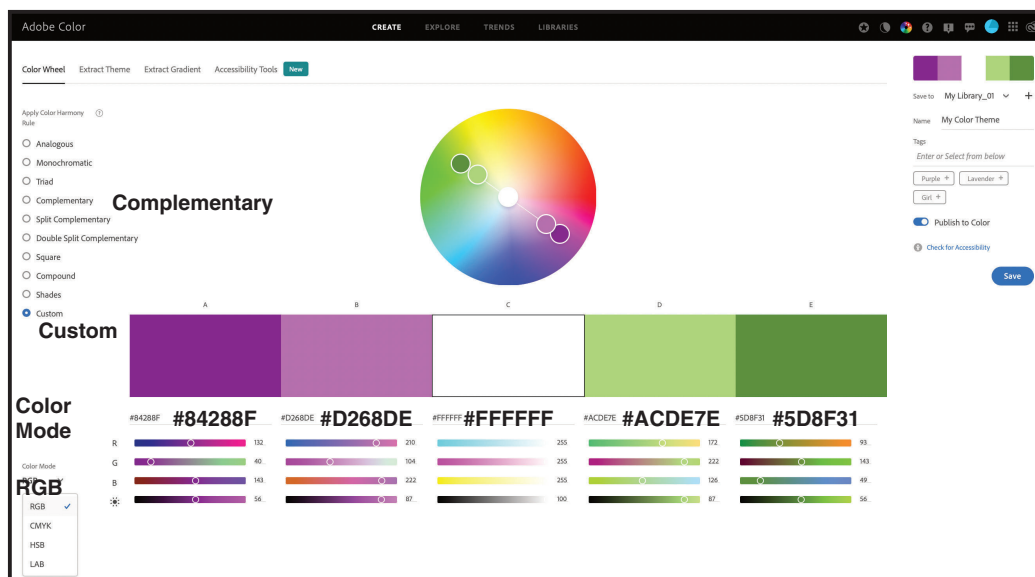
3. *Build Color Scheme. A Color Suggestion Tool Might Be Helpful:*

Color suggestion tools helped define the specific colors for this Purple-Green color scheme. A complementary color harmony was created with the Adobe Color tool [5].



Using the two-dimensional cross sections of the Munsell 10 GY and the Munsell 10 P hues to build a preliminary mock-up of the colorization efforts.

FIGURE 7.16 Using two-dimensional cross sections of the Munsell 10 GY and the Munsell 10 P hues to build a preliminary mock-up of the colorization efforts for modeling of DNA microarray data. Composite image created by Theresa-Marie Rhyne, 2024.



The Purple and Green color harmony with a white neutral color in Adobe Color. The color hex codes are shown under each color.

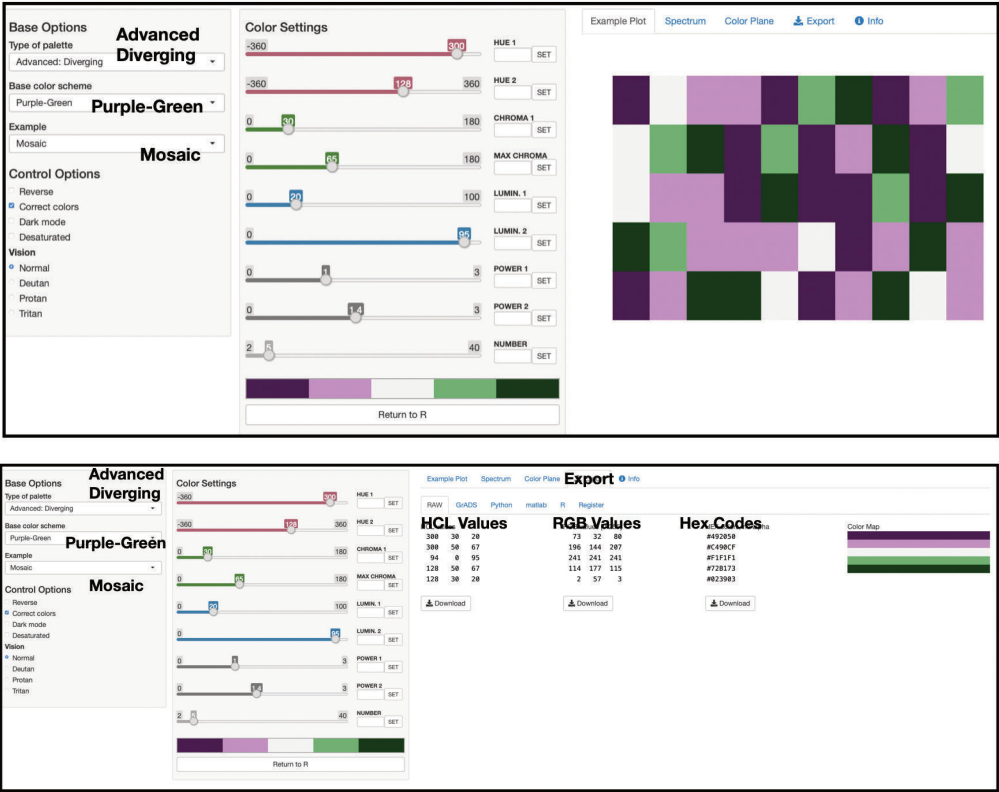
FIGURE 7.17 Using the Adobe Color app to create a Purple-Green color harmony divided by a neutral White element. The color hex codes are shown under each color element. Image created by Theresa-Marie Rhyne, 2024.

A diverging color scheme was built in the HCL Wizard system [13]. The results were compared with the final color scheme being a combination of both.

The Adobe Color Purple-Green color harmony was created by selecting the “Complementary” and the “Custom” options in the suggestion tool. A neutral White element divides the two colors. The color hex codes are specified under each color element. Figure 7.17 shows the results.

With HCL Wizard, the “Palette Generator” was used to locate the “Advanced Diverging” option and the “Purple-Green” base color scheme. The “Mosaic” example closely resembled the mosaic of DNA microarray data. Selecting the “Export” function provided specific HCL, RGB, or color hex codes for the selected Purple and Green diverging color scheme of five-color steps. Figure 7.18 shows these results.

The complementary color harmony provided a brighter solution, while the diverging color scheme provided a deeper solution. The Deep Purple hue of the diverging scheme had difficulties as there was a need to have some directional diagrams of the molecular structure embedded in each square of the mosaic. The Lime Green of the color harmony had the potential to provide an intensity challenge for viewing the directional diagrams as well. Figure 7.19 provides a visual comparison of the complementary color harmony and the diverging color scheme in the keys of Purple and Green. A middle ground began to be considered as the final color scheme solution. The next step was to check for color deficiencies for each color scheme.



The Purple and Green diverging color scheme with the mosaic example combined with the screen for selecting the export function for HCL, RGB, and color hex codes from HCL wizard.

FIGURE 7.18 Purple and Green diverging color scheme with the Mosaic example combined with the screen for selecting the Export function for HCL, RGB, and color hex codes from the HCL Wizard system. Composite image created by Theresa-Marie Rhyne, 2024.

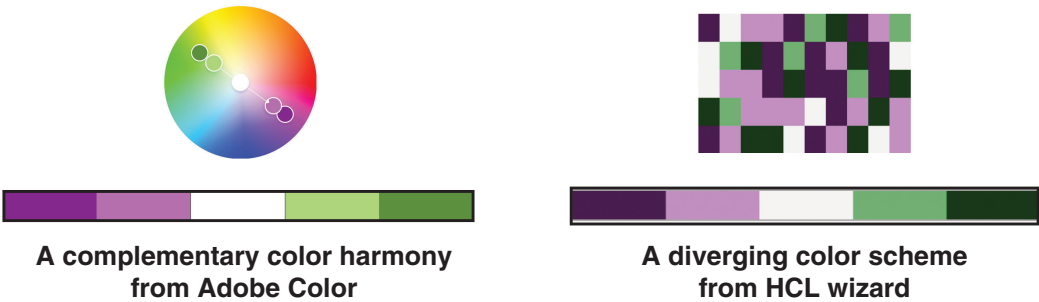


FIGURE 7.19 Comparison of the complementary color harmony and the diverging color scheme in the keys of Purple and Green. Composite image created by Theresa-Marie Rhyne, 2024.

4. *Check & Revise due to Color Deficiency, Contrasts, or Any Pre-Existing Conditions:*

Adobe Color and HCL Wizard provided their own approaches to checking for color deficiencies in their suggested color schemes. These checks determined whether a revision to address color deficiency would be necessary for either the complementary or diverging Purple and Green combinations. Let’s examine the results of each set of tests.

For the complementary color harmony, Adobe Color noted “No conflicts found – Swatches are Color Blind Safe” for their suggested Purple and Green combination. These results are shown in Figure 7.20.

For the diverging color scheme, HCL Wizard provided deuteranopia, protanopia, and tritanopia tests. The five-color Purple-Green combination passed these tests. These results are shown in Figure 7.21.

The Purple-Green color harmony from Adobe Color and the Purple-Green diverging color scheme from HCL Wizard both passed color deficiency checks respectively and did not need to be modified for these purposes.

5. *Apply Color Theme to Data Visualization. Some Modifications Might Result:*

The final version for the visualization of the correlation of large-scale molecular biological data with the Purple and Green color scheme is shown in Figure 7.22. The Purple-Green color harmony from Adobe Color and the Purple-Green diverging color scheme from HCL Wizard are shown underneath the data visualization. In this final solution, the Purple was adjusted in the direction of the complementary color harmony, while the Green was adjusted in the direction of the diverging color scheme.

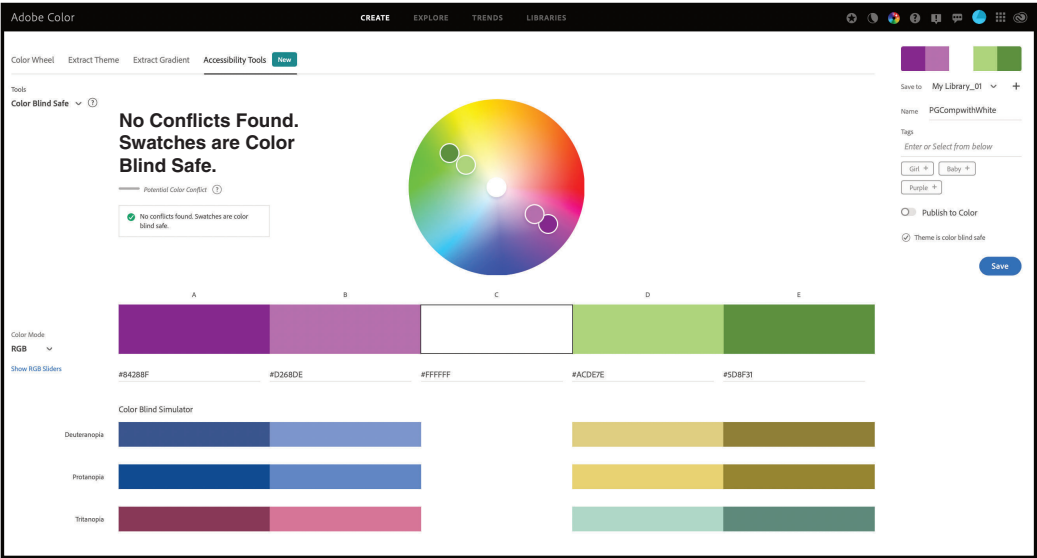


FIGURE 7.20 Adobe Color’s color deficiency tests for protanopia, deuteranopia, and tritanopia for the Purple and Green color harmony. The complementary color harmony passes the tests with “No Conflicts Found”. Image created by Theresa-Marie Rhyné, 2024.

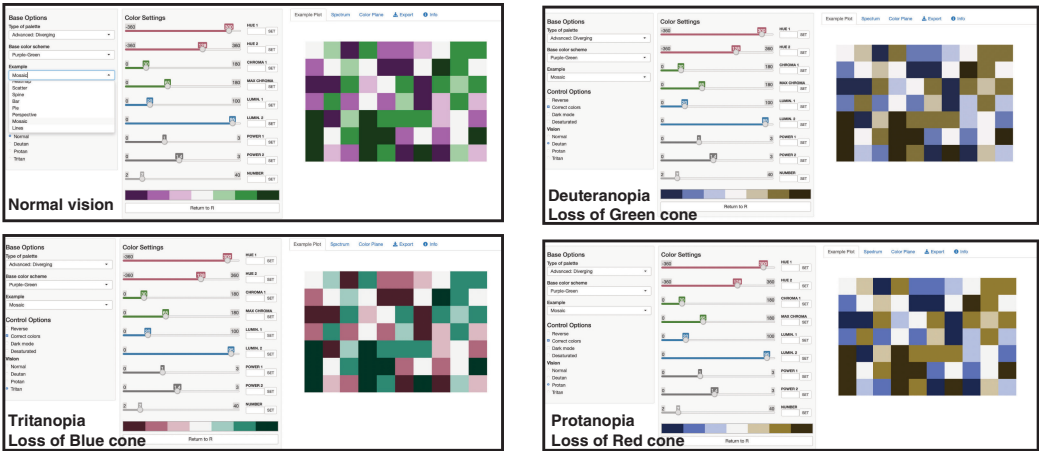


FIGURE 7.21 HCL Wizard's color deficiency tests for protanopia, deuteranopia, and tritanopia of the Purple-Green diverging scheme. The color scheme passes the tests. Composite image created by Theresa-Marie Rhyne, 2024.

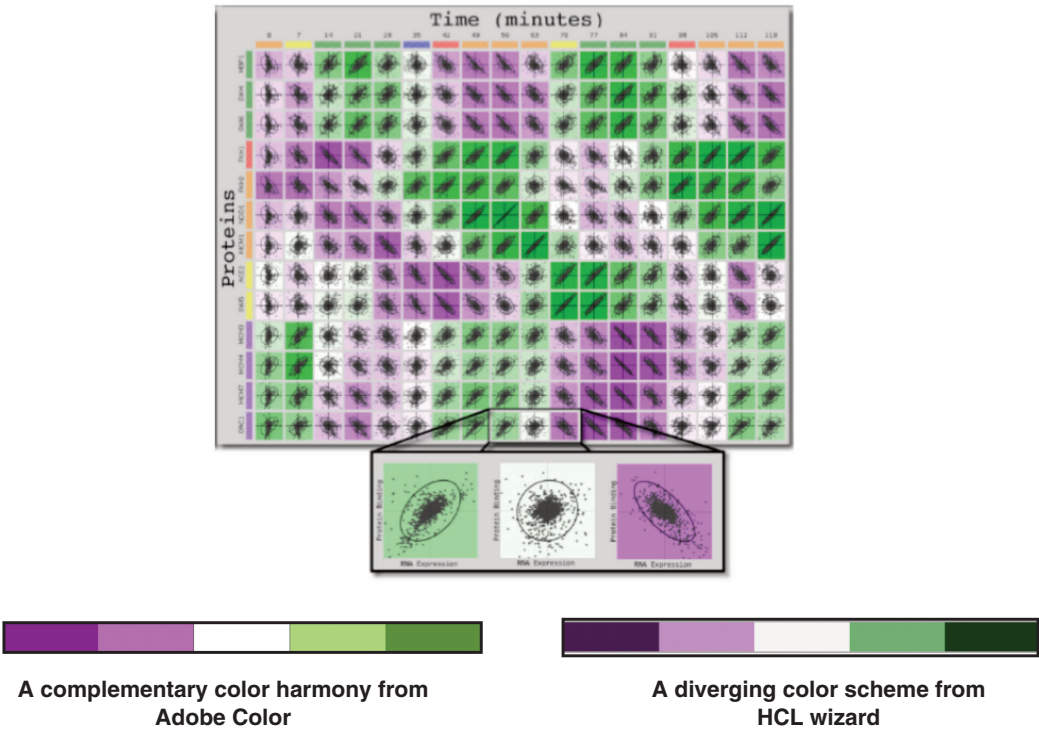


FIGURE 7.22 Finalized Purple-Green color scheme for the visualization of the correlation of large-scale molecular biological data with the original complementary color harmony and diverging color scheme. Composite image created by Theresa-Marie Rhyne, 2024.

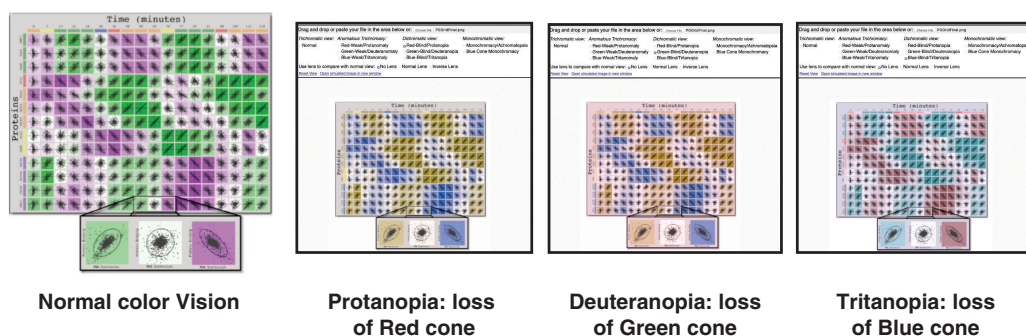


FIGURE 7.23 Using the Color Blindness Simulator (Coblis) to conduct color deficiency tests of protanopia, deuteranopia, and tritanopia for the finalized Purple-Green color scheme applied to the visualization of the correlation of large-scale molecular biological data. The color scheme passes the tests. Composite image created by Theresa-Marie Rhyne, 2024.

An additional color deficiency check was performed on the finalized Purple-Green color scheme using the Color Blindness Simulator (Coblis) tool [8]. These results are shown in Figure 7.23. Happily, the color deficiency checks indicated that a viewer with protanopia, deuteranopia, or tritanopia could effectively distinguish between Data Set #1 (Purple with normal color vision) and Data Set #2 (Green with normal color vision).

7.3.2 Review of Results for Identifying Patterns Associated with Correlation in Biological Data

In this case study, we have discussed how color theory concepts were applied to the visualization of correlation in large-scale molecular biological data. We showed how the merger of the (10 GY) Munsell Green-Yellow hue with the complement (10 P) Munsell Purple hue in the Munsell color order system served as a mock-up display for building a global view concept. Color suggestion tools helped define the specific colors for this Purple-Green color scheme. A complementary color harmony was created with the Adobe Color tool. A diverging color scheme was built with the HCL Wizard system. The five-stage colorization for data visualization process was applied to both color schemes. The results were compared with the final color scheme being a combination of both. Happily, all proposed color schemes passed color deficiency checks.

7.4 EXPLORING THE IMPACTS OF CLIMATE CHANGE IN TERMS OF THE DEVELOPMENT OF A TROPICAL STORM ANIMATION

The impact of climate change on the severity of tropical storms is a grand challenge research topic of interest at the national and international levels. Weather scientists have and continue to explore the impacts of warmer water temperatures, higher carbon dioxide levels in the atmosphere, and higher coastal water levels on future hurricane seasons. This type of research requires the use of supercomputers to run detailed simulations of real and theoretical tropical storm models (for further reading on such efforts, see Reference [14]).

High-resolution animations are produced from the resulting massive data sets to obtain increased understanding of the structural evolution of the tropical storms. Colorization of data elements helps in tracking the path of a particular parcel of air and in observing the different parameters associated with the tropical storm.

7.4.1 Building a Color Scheme for the Hurricane Animation Sequence

Here, we present a case study on building a color scheme for the time series animation sequence of a tropical storm or hurricane. A final movie was developed for the US Department of Energy, who funded these research efforts. Reference [15] highlights specific aspects of the movie project. The concepts presented here evolved from prior work with atmospheric and computational scientists with North Carolina State University and the Renaissance Computing Institute at the University of North Carolina at Chapel Hill. We explore specific aspects of this colorization effort using the five-stage process for colorizing a data visualization.

1. *Establish Data Classes for Visualization and Key Color for Visualization:*

Using a computational data set based on the Hurricane Katrina storm of 2005 [16], a *Perfect Storm* was simulated on a supercomputer using the Weather Research and Forecasting Model (WRF) [17]. The resulting data was then visualized with the VisIT tool, an open-source and freely available tool for Unix, Windows, and Macintosh workstations [18]. VisIT was originally developed by the US Department of Energy's (US DOE) Advanced Simulation and Computing Initiative (ASCI) to visualize and analyze results from extremely large computer simulations (<https://visit-dav.github.io/visit-website/>).

To build the *Perfect Storm* animation, several data sets were combined in VisIT to produce the visual effect of a hurricane. Each data set produced its own three-dimensional (3D) isosurface with its own unique color map. An isosurface represents points of constant value (e.g., pressure or temperature) within a volume of space. To produce the time series effect, each individual time step of the visualization was rendered and assembled to produce the final animated sequence. Playing back the complete time series in VisIT resulted in a “movie” or timelapse of the isosurfaces as the modeled hurricane progressed. Our meteorologists requested that the variance in the wind direction of the hurricane be depicted with wind vectors. The wind vectors are shown in conjunction with the evolution of the 3D isosurfaces. To examine how the various data elements came together to create the hurricane visual effect, our initial visualization efforts were in Gray scale. An example of these efforts is shown in Figure 7.24.

2. *Select Color Rule, Color Harmony per Criteria of your Data:*

The initial step in coloring the *Perfect Storm* visualization was to establish the basic color context for the build-up of the animation. Since the hurricane forms in the ocean, starting with a Blue background and allowing the 3D isosurfaces to develop seemed optimal. As Figure 7.24 shows, a dark color for the reference map was effective for indicating the geographic region while keeping the emphasis on the Gulf of

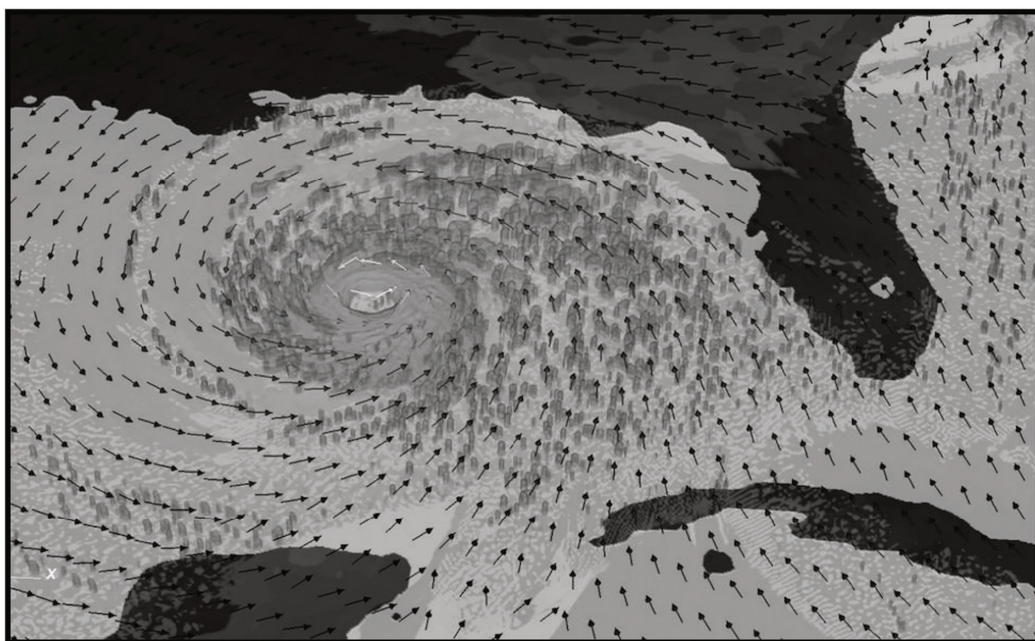


FIGURE 7.24 Grayscale frame from the Perfect Storm time series visualization with wind vectors shown. Visualization software engineering performed by Steve Chall while at the Renaissance Computing Institute at North Carolina State University (RENCI@NCSTU). Image created by Theresa-Marie Rhyne, 2024.

Mexico region as the storm develops. A deep shade of Blue was selected as the background color for this reference map.

The next step was to establish the color scheme to depict the 3D isosurfaces and the wind vectors. In the formation of the eye of the hurricane, two separate data sets merge to form the eye, while the wind vectors remain distinct. The visualization will require two colors for the isosurfaces that blend during the time series animation to form the eye of the hurricane and a high contrast color that continues to stand out for the wind vectors.

3. Build Color Scheme. A Color Suggestion Tool Might Be Helpful:

Turning to the ColorBrewer tool for suggestions, a four data class Purple and Orange diverging color scheme (<https://colorbrewer2.org/#type=diverging&scheme=PuOr&n=4>) was selected [19]. The Purple color represented the 3D isosurfaces, and the Orange color represented the wind vectors. We also examined the ColorBrewer option for evaluating whether a suggested color scheme can be viewed by individuals with color deficiencies. This is the “Eye” icon shown in the ColorBrewer software. Fortunately, the selected Purple and Orange color scheme passed this color deficiency test. Figure 7.25 shows the selected color scheme with the Black map border lines removed and the “Eye” color deficiency icon noted (please see Section 6.7 of Chapter 6 for further details on the use of ColorBrewer).

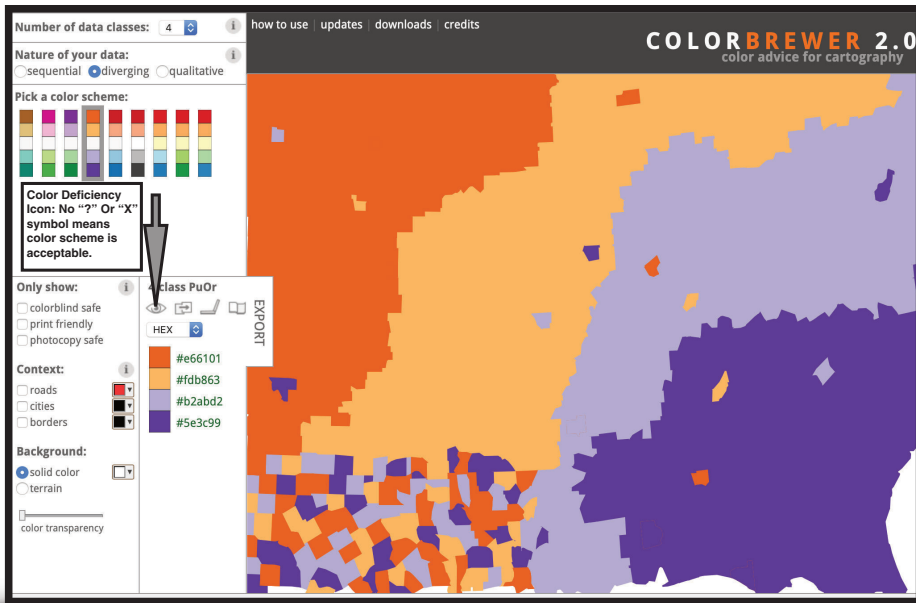


FIGURE 7.25 Purple-Orange diverging color scheme from the ColorBrewer color suggestion tool with map lines removed and the color deficiency icon noted. Image created by Theresa-Marie Rhyne, 2024, with the ColorBrewer 2.0 tool.

Using VisIT, two hurricane data sets fluctuated over a time series to establish the center of the hurricane. Each of the data points that formed the isosurfaces was defined as a dot or a pixel. In color theory, the concept of painting with dots or *pointillism* was developed by Impressionist painters in the 1880s [20]. The pixel has become fundamental to color display technologies of today [21]. Applying *pointillism* to the two hurricane data sets, Magenta dots and Blue-Cyan dots when combined in close proximity produced the visual appearance of a Purple isosurface. ColorBrewer was used to help diagram this color design concept. In Figure 7.26, sequential Magenta and sequential Blue-Cyan color schemes are shown to form a sequential Purple color scheme. This mixing functionality was not actually possible in the ColorBrewer tool itself [19].

4. Check & Revise due to Color Deficiency, Contrasts, or Any Pre-Existing Conditions:

We previously checked the four data class Purple and Orange diverging color scheme from ColorBrewer for color deficiency in step 3 and showed the results in Figure 7.25. The color scheme passed color deficiency tests.

5. Apply Color Theme to Data Visualization. Some Modifications Might Result:

Figure 7.27 shows a still image of the animation from the *Perfect Storm* data visualization in VisIT. The Magenta and Cyan-Blue data sets combined to produce a simulated Purple hurricane eye. The Orange wind vectors effectively



FIGURE 7.26 Using ColorBrewer to illustrate the concept of sequential Magenta and sequential Blue-Cyan colors visually blending to form the sequential colors of Purple. This mixing functionality is not actually possible in ColorBrewer. Image created by Theresa-Marie Rhyne, 2024, with the ColorBrewer 2.0 tool.

contrasted against the Purple hurricane and Blue Ocean elements. This allowed for observing the variance in the wind direction of the storm as the eye of the hurricane simulation develops. The complete time series movie of the Perfect Storm data entitled “WRF (Weather Research Forecasting) Simulation of Hurricane Katrina” is available as a video on YouTube (<https://www.youtube.com/watch?v=26Ws2aj8JOI&t=4s>) [22].

Using the Color Blindness Simulator (Coblis) tool [8], an additional color deficiency check was performed on a still frame from the animation of the *Perfect Storm* data. These results are shown in Figure 7.28. Fortunately, the color deficiency checks indicated that a viewer with protanopia, deuteranopia, or tritanopia could effectively distinguish the simulated hurricane eye and wind vectors from the background elements.

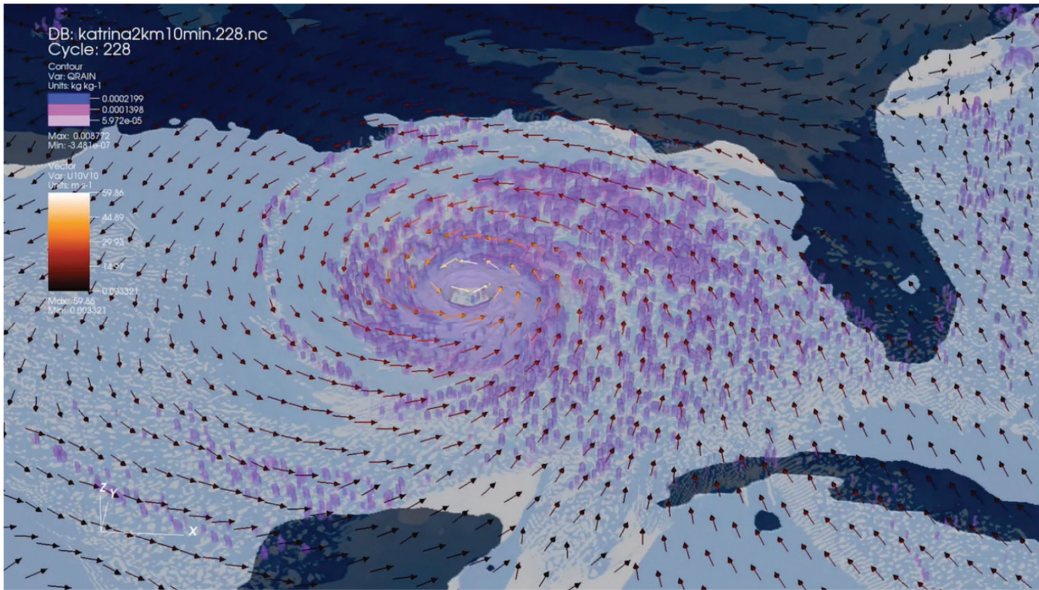


FIGURE 7.27 Still image of the animation from the Perfect Storm data visualization in VisIT. Image created by Theresa-Marie Rhyne, 2024.

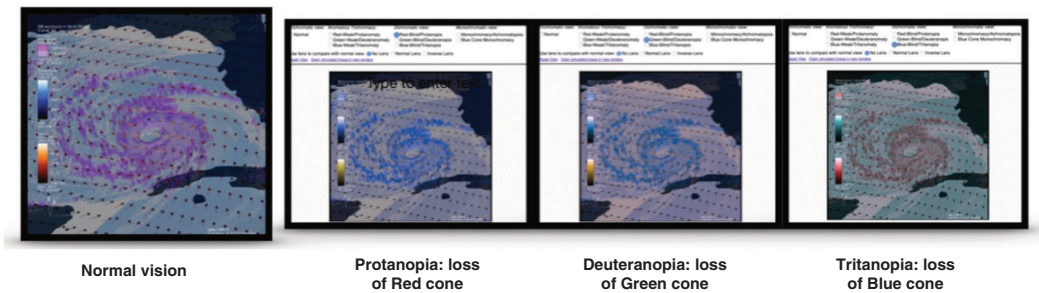


FIGURE 7.28 Using the Color Blindness Simulator (Coblis) for color deficiency checks of protanopia, deuteranopia, and tritanopia of a still frame from the animation of the Perfect Storm data. Composite image created by Theresa-Marie Rhyne, 2024.

7.4.2 Review of Results for Building a Color Scheme for the Hurricane Animation Sequence

In this case study, we showed how to build a color scheme for a time series animation of a *Perfect Storm* data visualization. The ColorBrewer suggestion system helped us define a Purple and Orange color scheme. We used the color theory concept of pointillism to create the Purple simulated hurricane eye from the merger of a Magenta-colored data set and a Blue-Cyan-colored data set. The wind vectors were colorized as Orange to remain

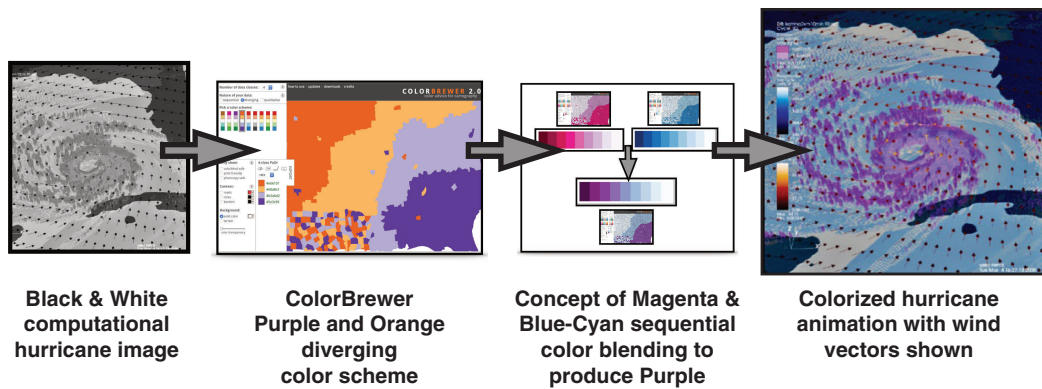


FIGURE 7.29 Flowchart of the process of colorizing the Perfect Storm animation. Composite image created by Theresa-Marie Rhyne, 2024.

distinct during the entire animation sequence. Fortunately, the color scheme passed color deficiency checks indicating that a viewer with protanopia, deuteranopia, or tritanopia could effectively distinguish the simulated hurricane eye and wind vectors from the background elements. Figure 7.29 shows the flowchart of this process.

7.5 CONCLUDING REMARKS

In this chapter, we defined a five-stage process for colorizing a data visualization. These steps are as follows: (1) *establish data classes for visualization and key color for visualization*; (2) *select color rule, color harmony per criteria of your data*; (3) *build color scheme. A color suggestion tool might be helpful*; (4) *check and revise due to color deficiency, contrasts, or any pre-existing conditions*; and (5) *apply color scheme to data visualization. Some modifications might result*. We developed a ring diagram to depict this process. Next, we asked ChatGPT, a generative AI system, to “*specify by color hex codes qualitative color schemes that pass color deficiency tests*” and successfully applied the two provided suggestions to our ring diagram. A specific color scheme was preferred and selected. We then applied the five-stage process to three case studies: (1) using color detection to identify fresh color schemes from everyday objects; (2) identifying patterns associated with correlation in biological data; and (3) exploring the impacts of climate change in terms of the development of a tropical storm animation. Each case study situation built upon the application of color theory fundamentals and color analysis tools noted earlier in this book. In Chapter 8, we will provide a general overview of each previous book chapter, highlighting the many color theory concepts and color analysis tools covered throughout the book.

REFERENCES

1. Hattab, G., Rhyne, T.M., and Heider, D. (2021), Ten simple rules to colorize biological data visualization. *PLOS Computational Biology*, 16(10), e1008259. <https://doi.org/10.1371/journal.pcbi.1008259>. pmid:33057327.
2. Rhyne, T.-M. (2021), From triad to qualitative: The process of colorizing a data visualization. *Nightingale, the Journal of the Data Visualization Society*. <https://nightingaledvs.com/from-triad-to-qualitative/>.

3. Open AI (2024), “ChatGPT 3.5”, <https://chat.openai.com>, accessed April 10, 2024.
4. Adobe Inc. (2024), “Color Palette Generator | Adobe Color”, <https://color.adobe.com>, accessed April 10, 2024.
5. Van Aelst, W. (1656–1657), “Vanitas Flower Still Life”, North. Carolina Museum of Art, https://commons.wikimedia.org/wiki/File:Vanitas_Flower_Still_Life_-_Willem_van_Aelst_-_Google_Cultural_Institute.jpg, accessed April 12, 2024.
6. Adobe Inc. (2024), “Adobe Capture”, <https://www.adobe.com/products/capture.html>, accessed August 23, 2024.
7. Meeks, E. and Lu, S. (2018), “Viz Palette”, <https://projects.susielu.com/viz-palette>, accessed April 14, 2024.
8. Coblindor (2021), “Coblis – Color Blindness Simulator”, <https://www.color-blindness.com/coblis-color-blindness-simulator/>, accessed April 15, 2024.
9. Alter, O. and Golub, G.H. (2004), Integrative analysis of genome-scale data by using pseudo-inverse projection predicts novel correlation between DNA replication and RNA transcription. *PNAS*, 1001, 16577.
10. Scientific Computing and Imaging Institute at the University of Utah (2016), “News from the SCI Institute”, <https://sci.utah.edu/>, accessed April 21, 2024.
11. Choudhury, A.M.M., Imroz, P., Kristin, R., Theresa-Marie, L., Yarden, J., Chris, R., and Alter, O. (2011), “Visualizing global correlation in large-scale molecular biological data.” Biovis 2011 Abstracts, *1st IEEE Symposium on Biological Data Visualization*, October 23–24, 2011, Providence, RI, http://biovis.net/2011/papers_abstracts/abstracts/120.html, accessed August 23, 2024.
12. Rhyne, T.-M. (2013), “Biological Data Visualization Using the Munsell Color System”, Color Blog of Munsell Color, <https://munsell.com/color-blog/biological-data-visualization-tools/>, posted in 2013, accessed August 23, 2024.
13. Ihaka, R., Murrell, P., Homik, K., Fisher, J.C., Stauffer, R., Wilke, C.O., McWhite, C.D., and Zeileis, A. (2020), “HCL Wizard Web Site”, <https://hclwizard.org>, accessed April 18, 2024.
14. Hill, K.A. and Lackmann, G. (2011), The impact of future climate change on TC intensity and structure: A downscaling approach. *Journal of Climate*, 24, 4644–4661.
15. Renaissance Computing Institute (2008), “The Future Perfect Storm”, <https://renci.org/news/the-future-perfect-storm/>, posted March 6, 2008, accessed April 21, 2024.
16. National Weather Service (2024), “Hurricane Katrina – August 2005”, <https://www.weather.gov/mob/katrina>, accessed April 22, 2024.
17. National Center for Atmospheric Research (2024), “Weather Research & Forecasting Model (WRF)”, <https://www.mmm.ucar.edu/models/wrf>, accessed April 22, 2024.
18. Lawrence Livermore National Laboratory (2024), “VisIT: Scalable, Open Source Visualization and Data Analysis from Laptop to LCF”, <https://visit-dav.github.io/visit-website/>, accessed April 22, 2024.
19. Brewer, C.A., Harrower, M., and The Pennsylvania State University and Axis Maps (2024), “ColorBrewer 2.0: Color Advice for Cartography”, <https://colorbrewer2.org/>, accessed April 23, 2024.
20. Mittal, S. (2023), “Pointillism: The Science of Color”, Paintshots, <https://www.paintshots.com/blogs/articles/pointillism-the-science-of-color>, accessed April 24, 2024.
21. Smith, A.R. (2021), *A Biography of the Pixel*, Cambridge, MA: MIT Press, Companion author web site: <http://alvyray.com/DigitalLight/default.htm>, accessed August 23, 2024.
22. Rhyne, T.-M. (2020), “Hurricane Katrina Visualization of 2008”, <https://www.youtube.com/watch?v=26Ws2aj8J0I&t=4s>, accessed April 24, 2024.

Review of Basic Concepts Covered

IN THIS BOOK, WE have highlighted principles of a body of knowledge called “color theory” and how to apply these concepts to creating digital media and visualization. The second edition has provided additional content including (1) a new chapter that translates between color harmony and data color schemes, (2) an expanded case study chapter with a five-stage process for colorizing data visualizations, and (3) examples of the use of generative AI for color scheme suggestion. In this final chapter of our journey, we review some of the highlights of each book chapter and note some key issues for future consideration.

8.1 HIGHLIGHTS FROM CHAPTER 1

We began our journey with a description of color models in Chapter 1. We showed that there are three basic color models: (1) the Red, Green, and Blue (RGB) color model for displays; (2) the Cyan, Magenta, Yellow, and Black (CMYK) color model for printing; and (3) the Red, Yellow, and Blue (RYB) color model for paints. We discussed how the process of moving between these color models is far from simple and results in mysterious discoveries about mixing colors. We showed that mixing Blue and Yellow yields Green with the RYB painters model while producing White with the RGB display model. Red is a secondary color in the CMYK color model and is created with Yellow and Magenta. Similarly, Blue is also a secondary color in the CMYK color model with Cyan and Magenta combining to produce it.

Next, we provided a brief overview of the historical progression of color theory and reviewed Isaac Newton’s creation of the color circle, Moses Harris’s pioneering detailed diagram of the Red, Yellow, and Blue color wheel, Johann Wolfgang von Goethe’s color wheel of complementary colors, and Michel Chevreul’s development of the theory of simultaneous contrasts. We also provided an example of applying Chevreul’s theories of color harmony to an Orange and Cyan contrasting color scheme for a treemap visualization. Chevreul was one of the first color theorists to write extensively on the notion that

Chapter 1: Visual summary

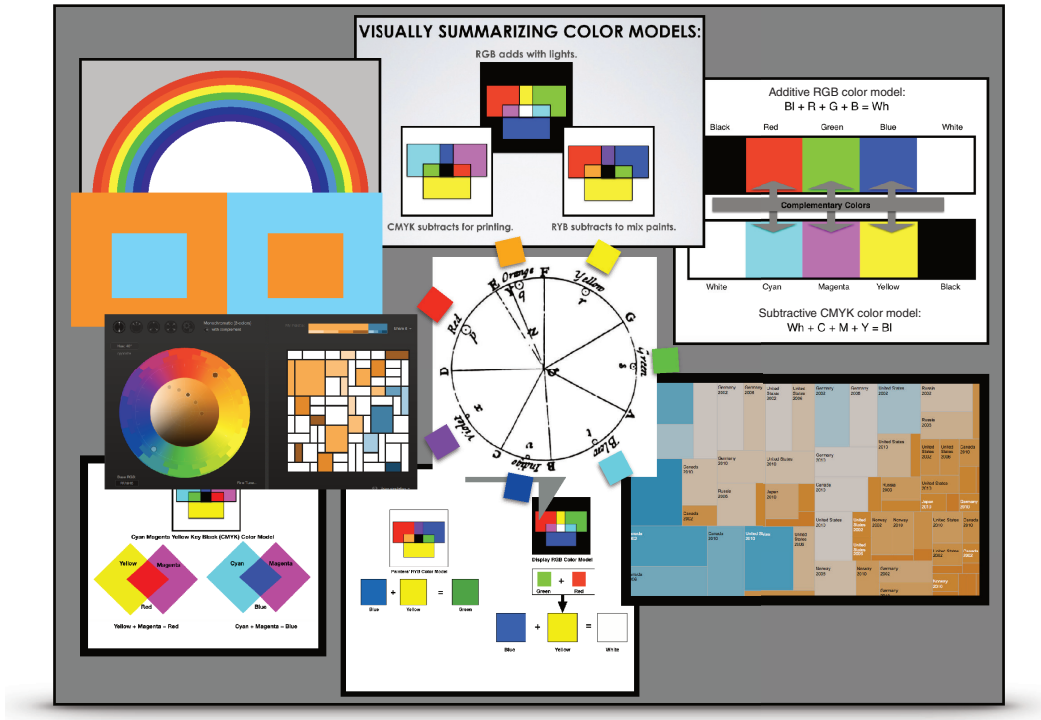


FIGURE 8.1 Visual summary of highlights presented in Chapter 1; refer to Chapter 1 for further details. Illustration by Theresa-Marie Rhyne, 2024.

the appearance of a given color changes according to the other hues surrounding it and its resulting context. Finally, we noted that none of these color models are perceptual models optimized for the human visual system. Human perception issues were examined in the late 1890s by Albert H. Munsell, an American artist and educator, when he developed his own color system. By the 1990s, the data visualization community began to note the potential for artifacts in data with the RGB color model. We indicated that Chapters 2 and 3 of this book will further discuss perceptual models for color. Figure 8.1 provides a visual summary of highlights from Chapter 1.

As we noted in Chapter 1, many concepts of color theory evolved based on the Red, Yellow, and Blue (RYB) color model of painters. At the end of Chapter 1, we referred you to these historic and key references on color theory. Stepping outside of digital media, we refer you to James Gurney's book on "Color and Light: A Guide for the Realist Painter" for a painter's perspective on the application of color [1]. For a photographer's perspective on working with RGB and CMYK color models, we refer you to Jerod Foster's book on "Color: A Photographer's Guide to Directing the Eye, Creating Visual Depth, and Conveying Emotion" [2].

8.2 HIGHLIGHTS FROM CHAPTER 2

In Chapter 2, we reviewed color vision principles such as trichromatic color vision and opponent color theory that together help explain how our eyes and brain process color information. We began the chapter by highlighting the visible spectrum of light with wavelengths of approximately 390–780 nm and ranging from Violet, Blue, Green, Yellow, Orange, and Red. An overview of human vision fundamentals noted that the key biological components of vision are the eye, the visual center in the brain, and the optic nerve that connects the two. We explored further the Young–Helmholtz theory of trichromatic color vision. This theory asserts that there are three types of cones and each is optimized to absorb a different spectrum range of visible light. One set of cones absorbs long waves of light in the Red range. A second set of cones absorbs middle waves of light in the Green range. The third set of cones absorbs short waves of light in the Blue range. Next, we reviewed Ewald Hering’s opponent color theory that challenged trichromatic color vision. Hering proposed that color vision occurred in three channels where opposite colors are in competition and do not mix. These channels are (1) a Red-Green channel, (2) a Yellow-Blue channel, and (3) a Black-and-White channel. We showed how color vision researchers, Leo Hurvich and Dorothea Jameson, demonstrated that the theories of Young–Helmholtz and Hering co-existed together. Young and Helmholtz’s theory of trichromatic color vision explains what happens with our eyes at the photoreceptor level. Hering’s opponent processing color theory explains aspects of color vision processing at the neural level when images are transferred from the eye to the brain via the optic nerve.

We went on to explore how we have three independent channels for conveying color information to our brain or trichromacy. We worked through an example showing that the brain requires at least two of these channels for color vision. We also examined how the brain has no means of distinguishing between a set of single wavelengths and a set of wavelengths combined that produce the same color. This concept of metamerism is used in engineering electronic displays that we use on a daily basis. Colorimetry, the science of color measurement and matching, was introduced, as well as luminosity, the perceived brightness of a color. We showed that Magenta is not one of the colors that spans the Violet, Blue, Green, Yellow, Orange, and Red visual spectrum. Visually, we are certain that the color is between Violet and Red, but it has no specific wavelength. Our brains create Magenta to logically fill in the color gap between Violet and Red.

We continued Chapter 2 with a discussion of color deficiencies or color blindness. We reviewed the key color deficiencies of Red-Green (protanopia), Green-Red (deutanopia), and Blue-Yellow (tritanopia). Online tools that provide assistance in showing what images look like to individuals with color deficiencies were reviewed. Additionally, we worked through an example of applying color deficiency studies to a color wheel (or pie chart) that also represents the primary and secondary colors of the Red, Yellow, and Blue color model. These colors on the wheel include Red, Orange, Yellow, Green, Blue, and Purple. Our color deficiency simulation showed how individuals with color deficiencies are unable to easily distinguish between these six colors.

Chapter 2: Visual summary

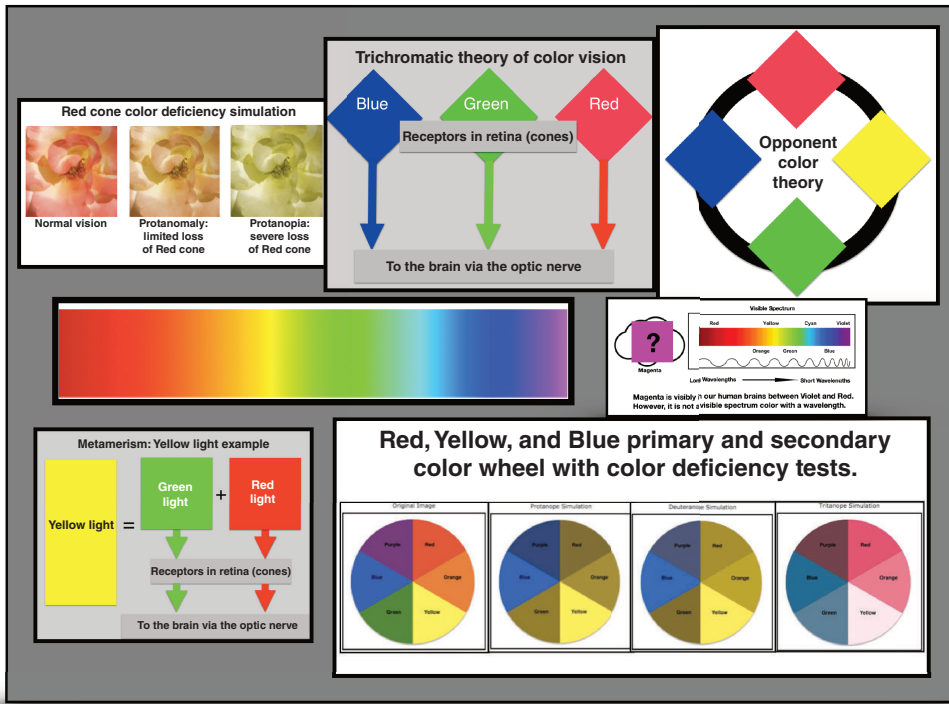


FIGURE 8.2 Visual summary of highlights presented in Chapter 2; refer to Chapter 2 for further details. Illustration by Theresa-Marie Rhyne, 2024.

Finally, we discussed how the use of a rainbow color map in visualizing data potentially produces perceptual errors in analyzing trends in the data. This is due to the non-perceptual uniformity of the distances between the Red, Orange, Yellow, Green, Blue, Indigo, and Violet hues in the color spectrum. At the end of Chapter 2, we noted references and further reading associated with these topics. Figure 8.2 provides a visual summary of highlights from Chapter 2.

8.3 HIGHLIGHTS FROM CHAPTER 3

In Chapter 3, we reviewed various color gamut, color spaces, color notation systems, and colorimetry concepts that are used widely in color analysis, design, and reproduction. The chapter provided the terminology to understand online and mobile color apps that allow for digital color selection and capture. We noted that color gamut is defined as the range of colors a device can reproduce and almost every device has a different color gamut. Color images on one device like your mobile phone will look different when printed from your inkjet printer due to the different range of colors of the respective devices. The devices have different color spaces as well since a mobile phone's color space is defined by the

RGB display model and the inkjet printer's color space is defined by the CMYK printers model. We reviewed the device independently and commonly applied RGB color spaces of sRGB, Adobe RGB, and ProPhoto RGB. The sRGB color space approximates the color gamut of most RGB display devices. Many software applications and Web specifications are designed around the sRGB specification. Adobe RGB is aimed at providing fewer challenges in transferring from RGB display devices to CMYK printing output devices. ProPhoto RGB is designed to offer a color gamut larger than sRGB to support the requirements of high-end digital photography.

Next, we examined the concepts of colorimetry, a system of color measurement based on the concept of equivalent-appearing stimuli to human eyes. Colorimetry data is gathered from empirical studies of humans matching colors. The task of each human subject is to use the three primary lights of RGB to match a designated “reference” color. When a match is established, the reference color can then be defined in terms of the amount of the respective RGB lights required to reproduce the equivalent reference color.

Colorimetry studies formed the foundation for the CIE 1931 color space, developed to be independent of devices or other means of emission or reproduction of color. We highlighted the CIE 1931 color space and discussed its perceptual uniformity limitations that resulted in the creation of CIE LUV and CIE LAB in 1976. The CIE LUV color space was designed specifically for emissive colors that correspond to images captured by a camera or created by computer graphics rendering programs. As a result, CIE LUV is used in the display industry. The CIE LAB color space was developed to characterize color surfaces and dyes. CIE LAB is used widely in the color imaging and printing industries.

Next, we highlighted the concept of color appearance models. Colorimetry is focused on examining whether colors appear to match under a defined set of viewing conditions. Our eyes receive color under a variety of viewing conditions beyond these XYZ tristimulus values. A color appearance model (CAM) provides mathematical or numerical descriptions of how the appearance of colors changes in different viewing situations. The CIE LUV and CIE LAB uniform color spaces were tentative numerical steps to model hue, lightness, chroma, and saturation to address color appearance. Researchers in the 1980s and 1990s began to develop CAM systems beyond these initial efforts. In 1997, CIECAM97s was successfully introduced as an interim comprehensive model but was difficult to use. CIECAM02, after academic and industry assessments, was released in 2002. CAM16 was a 2016 successor of CIECAM02 with various fixes and improvements. In 2020, a uniform color space that combined the similar structure of CIE LAB with improved CAM16 data was introduced as Oklab. As of 2023, Oklab gained acceptance and is supported in Web browsers.

We went on to discuss the Munsell color system, a three-dimensional model that defines color as having three attributes: hue, value, and chroma. Albert H. Munsell, an American artist and art educator, developed the color order system in the 1890s to establish a notation of color with systematic order that stepped beyond what he called “misleading” color names. The system is built on equally perceived color differences in the shape of branching geometry defined as a color tree. The Munsell color order system has served and continues to serve as the basis for a variety of government and industry specifications.

Then, we examined hue, saturation, and value (HSV) and hue, saturation, and lightness (HSL) color spaces. These three-dimensional cylindrical coordinate representations of the RGB color model were established to create intuitively easier and more perceptually relevant mixing of additive RGB color lights. Many “*color picking*” tools on digital devices have been based on these color models. Members of the computer graphics community developed HSV and HSL.

Hue, chroma, and luminance (HCL) color spaces that are tailored to human color perception and attempt to address perceptual uniformity were then introduced. A color space is perceptually uniform if a change of length in any direction X of the color space is perceived by a human as the same change. A non-uniform perceptual color map can have stark contrasts when transitioning from one hue to another hue. RGB, HSV, HSL, and CIE XYZ, while having many advantages, are not perceptually uniform. The Munsell, CIE LUV, and CIE LAB represent attempts at creating human perceptual uniform color spaces. HCL, sometimes referred to as lightness, chroma, and hue (LCH), color spaces merge many of the concepts of other color spaces. Similar to how HSV and HSL transform RGB spaces by extending two-dimensional polar coordinates to three dimensions, HCL spaces perform cylindrical transformations of CIE LUV or CIE LAB for optimized perceptual uniformity. These HCL color spaces are frequently referred to as *polarized* CIE LUV or *polarized* CIE LAB. When the RGB and HCL color spectrums are converted to Grayscale diagrams, it is easier to conceptualize the uneven nature of the RGB color space and the nearly consistent nature of the HCL color space.

From there, we covered Web colors, noting that the initial World Wide Web Consortium (W3C) color specifications were based on the sRGB color model. The current CSS Color Module Level 4 specification allows a *Web color* to be specified in a variety of ways according to many of the color spaces covered in Chapter 3. These include RGB, HSL, CIE LAB, LCH, Oklab, and Oklch. In setting parameters for displaying Web pages, colors can be defined according to the format of these color spaces or in the hexadecimal (hex triplet) format. A hex triplet is a six-digit and three-byte hexadecimal number used to represent a color and is frequently referred to as a *color hex code*. Most color selection tools and apps include RGB and *color hex code* formats at a minimum. We then provided an example of using *color hex codes* with the Chat Generative Pre-trained Transformer (*ChatGPT*) text-based generative AI tool. We also reviewed Web safe colors and provided an example of Web color selection with the Color Companion mobile app.

The final color space we reviewed was the Pantone color matching system (PMS), a proprietary color space used primarily in printing and graphics design. Pantone matching methods utilize the Pantone numbering system to identify colors. Individuals located in different geographic locations can refer to particular PMS values to insure that colors match without making direct personal contact with each other. The Pantone color guides originally consisted of narrow cardboard sheets (approximately 6 by 2 inches or 15 by 5 cm) that were printed on one side with rectangular samples showing the different Pantone colors. The guide was bound together at the one end to allow for opening the strips out in a fanlike manner. Updated versions still exist today. Pantone also provides

an online and mobile Pantone Connect app. The app provides digital color swatches of the Pantone Color Guide, for creating a color palette from scratch. The Pantone Connect app also allows for capturing colors from a digital image or photograph located on a mobile phone. The app provides data about the Lab (CIE Lab), sRGB, color hex code, and CMYK values of specified Pantone color swatches. We worked through an example of how the addition of Pantone inks can restore the vibrancy of color schemes originally designed in the RGB space and transferred to the CMYK space for printing. We also showed how to use the Pantone Connect app to explore color data and color harmonies for a given Pantone hue.

It is important to continue to remember a key concept about color gamut: viewing a color in digital or virtual color spaces does not always mean that the color will appear the same in printed or physical color spaces. This is because of the differences in the RGB color model for display, the CMYK color model for printing, and the RYB color model for painting. Although physical comparison of color specimens to carefully prepared paint chips or color samples can be considered out of date with regard to digital media, it turns out to be one of the more accurate methods of color matching. This is because any digital color library cannot depict color specimens consistently or accurately due to the color gamut constraints of RGB display devices. Figure 8.3 provides a visual summary of highlights from Chapter 3.

Chapter 3: Visual summary

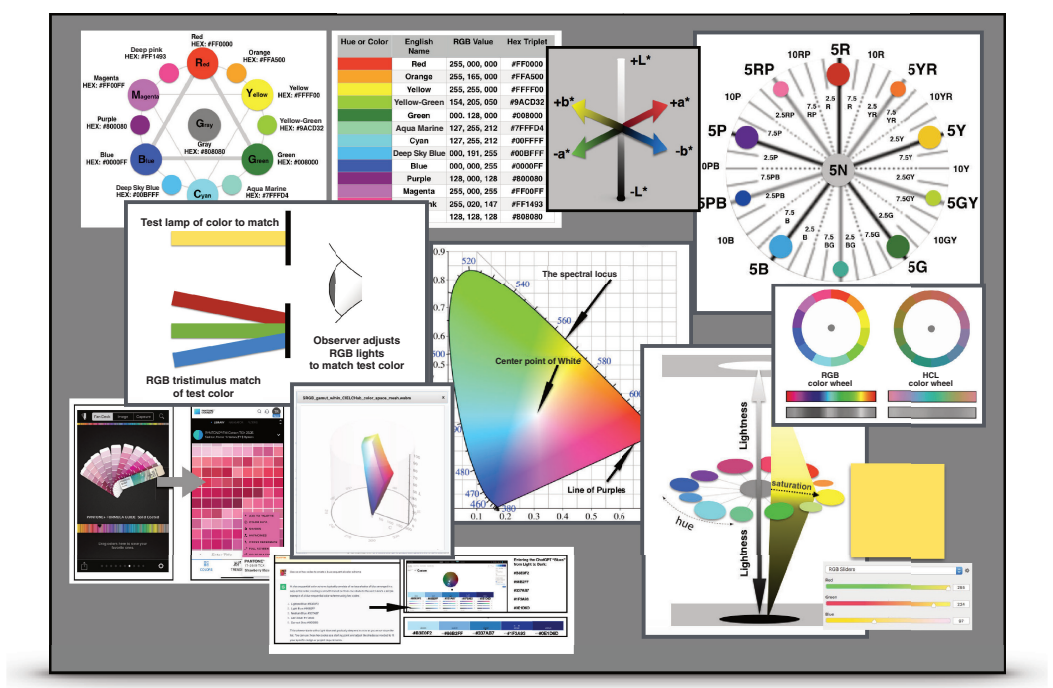


FIGURE 8.3 Visual summary of highlights presented in Chapter 3; refer to Chapter 3 for further details. Illustration by Theresa-Marie Rhyne, 2024.

8.4 HIGHLIGHTS FROM CHAPTER 4

In Chapter 4, we defined the language of color harmony based on the color wheel and colorized infographic examples using color harmony principles. We began with a review of the steps for constructing the RGB color wheel for displays, the CMYK color wheel for printing, and the RYB color wheel for painting. We showed how the RGB and CMYK color wheels are inversely related and collapse into one RGB/CMYK color wheel. We defined the primary colors, secondary colors, and tertiary colors for each wheel and diagrammed them as well. We defined the hues, tints, tones, and shades of colors. Hues are the brightest and purest form of colors and reside on the outside of the color wheel. Tints are hues mixed with White and resided on a tint ring next to the hue colors. Tones are hues mixed with Gray and reside on the third tone ring next to the tint ring. Shades are hues mixed with Black and reside on the inner shade ring between the tone ring and the neutral zone of Gray on the color wheel. We then described warm and cool colors on the color wheel.

Next, we defined color harmony as the process of choosing colors, from the color wheel, that work well together in the composition of an image. Nine types of color harmony with an example for each were presented: (1) monochromatic; (2) analogous; (3) complementary; (4) split complementary; (5) analogous complementary; (6) double complementary; (7) tetrad – rectangular and square; (8) diad; and (9) triad. We then reviewed a color wheel or gamut masking approach to defining a specific range of colors or color harmony and showed how to use the Gamut Mask Tool developed by James Gurney and Richard Robinson.

We revisited the historical evolution of the color wheel and color harmony building on our preliminary review in Section 1.4 of Chapter 1. In Section 4.7, we provided more details of contributions by Isaac Newton, Moses Harris, Johann Wolfgang von Goethe, and Michel Chevreul. We introduced Phillipp Otto Runge's color sphere contribution and how it initially influenced Albert Munsell's efforts, as well as impacted the teachings at the Bauhaus art school. We reviewed the writings of George Field and Ogden N. Rood on chromatics and color harmony that influenced painters, especially Impressionists, of their time. Next, the contributions of Louis Prang and Milton Bradley to art education at the elementary and secondary levels, using the RYB color wheel, were noted. We then highlighted teachings of the preliminary course and color concepts at the Bauhaus school, which operated in Germany and combined a unique approach to design with crafts and fine arts. In the Bauhaus discussion, we featured the teaching of color concepts by Paul Klee, Wassily Kandinsky, Johannes Itten, and Josef Albers. We concluded our historical evolution featuring Josef Albers's *Interaction of Color* book from Yale University Press that has now been modernized into a website. Albers's exercises, taught by hands-on application, demonstrated the concept that the appearance of a color changes according to its context and is greatly influenced by the other hues and lighting surrounding it.

Color harmony concepts have been applied to many disciplines. In our discussion of the historical evolutions of the color wheel, we highlighted a few individual contributions oriented toward the Western World. As you explore color theory further, you may find inspiration from other contributors and disciplines. Reference [3] provides a discussion of color theory from the interior design and architecture perspective. Figure 8.4 provides a visual summary of highlights from Chapter 4.

Chapter 4: Visual summary

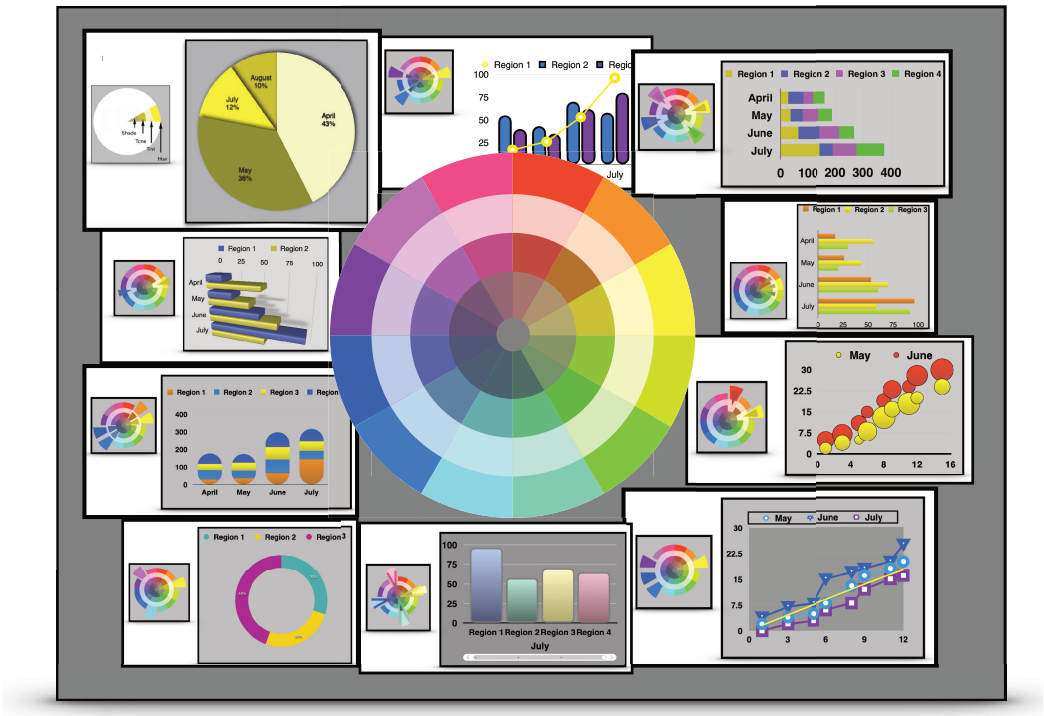


FIGURE 8.4 Visual summary of highlights presented in Chapter 4; refer to Chapter 4 for further details. Illustration by Theresa-Marie Rhyne, 2024.

8.5 HIGHLIGHTS FROM CHAPTER 5

In Chapter 5, we introduced the concept of data color schemes and how they relate to color harmony fundamentals. As previously noted, color harmony is a language based on the color wheel for designing color schemes. In the field of data visualization, there is a different approach to building color palettes based on the kind of data you are examining. These *data color schemes* are divided into three types of classifications: (1) sequential, (2) diverging, and (3) qualitative. Sequential schemes are designed for ordering numeric information where colors progress from low to high (or vice versa). Diverging schemes emphasize quantitative data that progresses outward from a central neutral midpoint to two different color extremes. Qualitative schemes are designed for coding categorical information when there is no particular ordering of the data and colors should receive equal perceptual weight. The concepts of data color schemes were conceptualized by Cynthia Brewer.

Sequential color schemes are optimized for ordered data such as temperature, elevation, income, or infection rates. The standard convention is for the sequence to progress from a light color, representing low attribute values, to a dark color, representing high attribute values. These sequences are composed of either a single-hued or multi-hued progression.

A *monochromatic* color harmony combines one hue (a 100% saturated color) with various tints, tones, and shades of that hue to create a color scheme. This harmony pairs well with the concept of a *single-hue sequential* sequence that progresses from light to dark. An *analogous* color harmony refers to selecting colors that are next to each other on the color wheel. *Multi-hue sequential* color schemes are sequences of colors that progress from light to dark and are also adjacent to each other on the color wheel. Thus, the *analogous* color harmony pairs effectively with *multi-hue sequential* color schemes.

Diverging color schemes place equal emphasis on both a specified mid-range value and two extreme critical values. They are created by joining two sequential color sequences together with a neutral midpoint. Depicting temperature data values that are either cold or hot with a neutral midpoint, elevation data that is either above or below sea level, or voter responses that are either for or against an issue with uncommitted responses in the middle are effective uses of *diverging* color schemes. The *complementary* color harmony combines two colors that oppose each other on the color wheel and matches well to *diverging* color schemes. However, there are many examples of *diverging* color schemes that are not complementary color harmonies such as Purple-Orange and Red-Blue schemes.

Qualitative color schemes use colors to label different categories of data. There are no implied magnitude differences between each of the categories. A mapping of different routes on a subway, equivalent steps on a flowchart, or types of vegetables in a market are examples of visualizing *qualitative* data. There should be no large variances in lightness or saturation of colors since that can signify importance or preference for a particular category. The *triad* color harmony is well suited for a *qualitative* color scheme with three categories of data. The three colors in the triad color harmony are evenly spaced on the color wheel at 120° apart. This placement produces three distinctive and distinguishable colors with equal variances. The *square* color harmony facilitates the building of a qualitative color scheme with four categories of data. The four colors in a square color harmony are equidistant at 90° apart on the color wheel.

In general, it is not difficult to build a *qualitative* color scheme to support up to four distinctive and distinguishable colors that will be considered color-blind safe. However, moving to ranges between five and eight colors becomes extremely challenging. After eight colors, even normal color vision individuals find it difficult to distinguish between all colors in the color palette. Interestingly, traditional color harmonies rarely go beyond four distinctive and distinguishable colors as well. In situations where *qualitative* color schemes of five or more colors are used, one approach to address these color deficiency concerns is to enhance the visualization with text or numeric labeling for each color variable. This double coding of data allows for referring to the individual elements by color, number, and label.

After exploring how data color schemes and color harmony related to one another, we showed how to use *Adobe Firefly*, a generative AI system, to build a sequential color scheme based on the fundamentals of color harmony. We also showed how the *ChatGPT* generative AI tool provides color hex code suggestions for *diverging* color schemes. Figure 8.5 provides a visual summary of highlights from Chapter 5.

Chapter 5: Visual summary

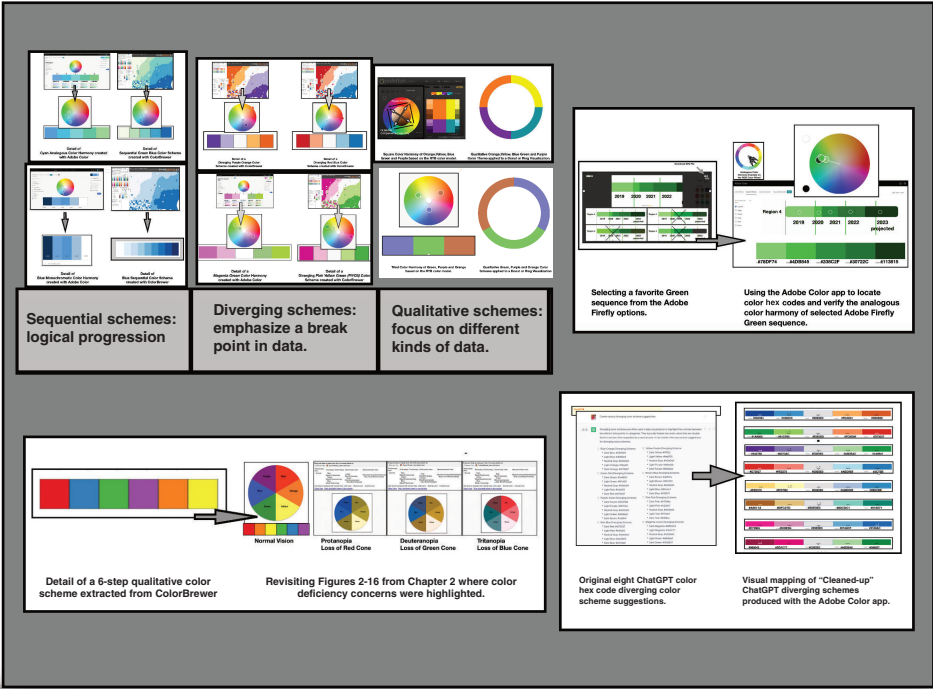


FIGURE 8.5 Visual summary of highlights presented in Chapter 5; refer to Chapter 5 for further details. Illustration by Theresa-Marie Rhyne, 2024.

8.6 HIGHLIGHTS FROM CHAPTER 6

In Chapter 6, we have examined eight tools for analyzing and creating color palettes. These include (1) Adobe Color; (2) Adobe Capture; (3) the COLOURlovers community and its Color Palette Software (COPASO) tool; (4) Paletton's Color Scheme Designer; (5) Viz Palette; (6) ColorBrewer 2.0; (7) HCL Wizard; and (8) Data Color Picker. We discussed key features of each tool and showed how each respective tool can be used to analyze or create a color palette. Adobe Color allows for importing a digital image, as well as creating and analyzing a color scheme directly from an RGB/CMYK color wheel. The Viz Palette online app facilitates viewing how generic data visualizations might appear with a given color scheme. The Data Color Picker online tool allows for quickly building sequential, diverging, and qualitative color schemes with specified color hex codes. Many tools incorporate color deficiency checks into their analyses. These include the Adobe Color, Paletton Color Scheme Designer, ColorBrewer, HCL Wizard, and Viz Palette. Other color tools provide minimal automated color suggestion and prefer to allow users to individually select or navigate to the desired colors of choice in the imported image. The COLOURlovers' COPASO online application works in this way.

Each tool has its own approach for aiding in creating and assessing color schemes. As you continue on in your color studies, you will likely find additional color applications that

Chapter 6: Visual summary

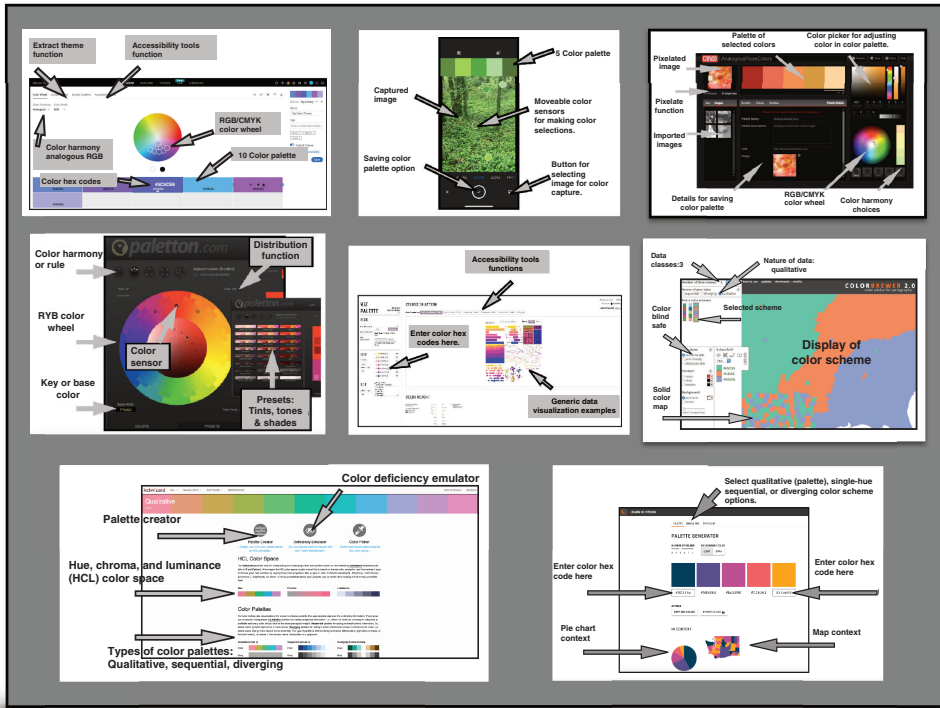


FIGURE 8.6 Visual summary of highlights presented in Chapter 6; refer to Chapter 6 for further details. Illustration by Theresa-Marie Rhyne, 2024.

work as part of your own digital color toolbox. One paper application worth considering is a pocket or larger color wheel from “The Color Wheel Company”. This pocket color wheel is 5.125 inches in diameter, while a larger size is 9.25 inches in diameter [4]. Figure 8.6 provides a visual summary of highlights from Chapter 6.

8.7 HIGHLIGHTS FROM CHAPTER 7

In Chapter 7, we defined a five-stage process for coloring a data visualization. These steps included the following:

1. Establish data classes for visualization and key color for visualization;
2. Select color rule, color harmony per criteria of your data;
3. Build color scheme. A color suggestion tool might be helpful;
4. Check and revise due to color deficiency, contrasts, or any pre-existing conditions;
5. Apply color scheme to data visualization. Some modifications might result.

We developed a ring diagram to depict this process.

Chapter 7: Visual summary

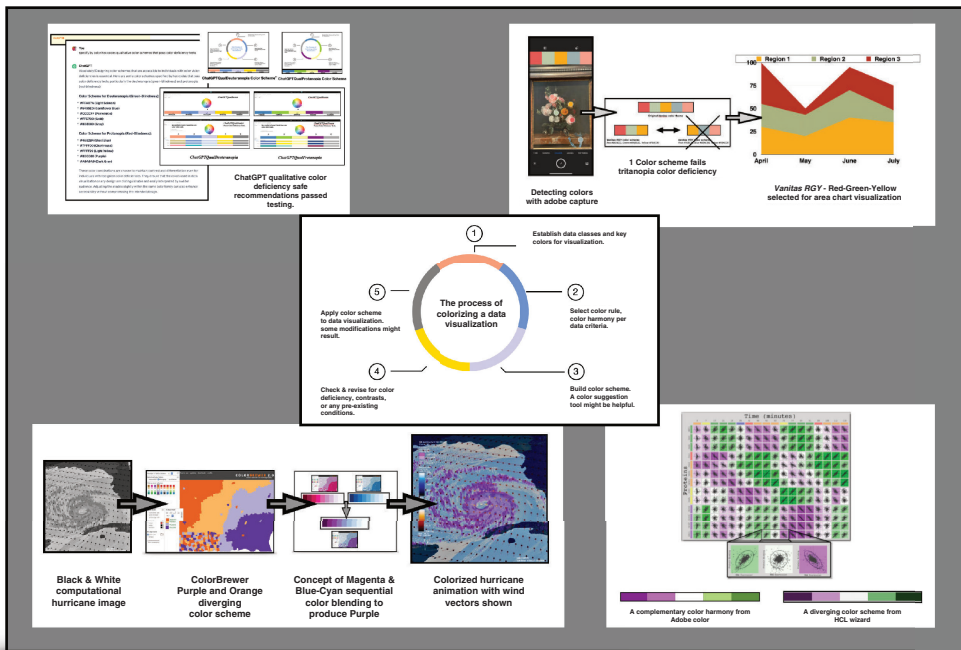


FIGURE 8.7 Visual summary of highlights presented in Chapter 7; refer to Chapter 7 for further details. Illustration by Theresa-Marie Rhyne, 2023.

Next, we asked ChatGPT, a generative AI system, to “*specify by color hex codes qualitative color schemes that pass color deficiency tests*” and successfully applied the two provided suggestions to our ring diagram. A specific color scheme was preferred and selected.

We then applied the five-stage process to three case studies: (1) using color detection to identify fresh color schemes from everyday objects; (2) identifying patterns associated with correlation in biological data; and (3) exploring the impacts of climate change in terms of the development of a tropical storm animation. These three examples demonstrated how several of the color tools noted in Chapter 6 could be combined for color analyses, including color deficiency assessments. Each case study situation built upon the application of color theory fundamentals and color analysis tools noted earlier in this book. Figure 8.7 provides a visual summary of highlights from Chapter 7.

8.8 CONCLUDING REMARKS

In this book, we have provided an overview of the fundamentals of color theory and terminology associated with color science. We defined the language of color harmony based on the color wheel and the concept of data color schemes. We showed how to translate between these two principles. Additionally, some historical perspective on the evolution of color theory, from the Western World viewpoint, was provided. Next, we showed how these fundamentals are incorporated into online and mobile color apps that allow for

digital color selection and capture. Although we have shown several approaches to color scheme development, the creation of a specific color palette is targeted at the needs and requirements of the particular project that is underway. Our suggestions are color advice with the final solutions being your choices of color selection for your unique tasks and objectives. We have only begun to introduce concepts of color theory as applied to digital media and visualization in this book. We hope you continue to have your own discoveries exploring the world of color that surrounds us.

REFERENCES

1. Gurney, J. (2010), *Color and Light: A Guide for the Realist Painter*, Kansas City, MO: Andrews McMeel Publishing.
2. Foster, J. (2014), *Color: A Photographer's Guide to Directing the Eye, Creating Visual Depth and Conveying Emotion*, San Francisco, CA: Peachpit Press.
3. Sickler, D. (2010), *The Keys to Color: A Decorator's Handbook for Coloring Paints, Plasters and Glazes*, Seattle, WA: Createspace Independent Publishing Platform.
4. The Color Wheel Company (2024), "Color Wheels", <https://colorwheelco.com/products/>, accessed April 30, 2024.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Index

Note: *Italic* page numbers refer to figures.

- Adams-Nickerson-Stultz formula 52
- Adobe Capture 132, 137, 137–138, 138, 198
- Adobe Color 133, 198
 - capturing color scheme from image 135–136
 - creating color schemes 134–135
- Adobe Creative Cloud software services 133
- Adobe Firefly 126–127, 127–129
- Adobe Kuler *see* Adobe Color
- Adobe RGB 43, 192
- Albers, Josef 113–114
- analogous complementary harmony 95–98, 97, 98
- analogous harmony 91, 93, 94, 119

- Black-White channel 23
- Blue cone color deficiency 33
 - simulation 33
- Blue monochromatic color harmony 120
- Blue sequential color scheme 120
- Blue-Yellow (tritanopia) deficiency 35, 190
- Bradley, Milton, color wheel instruction writings 111–112
- Brewer, Cynthia 149

- cartography *see* ColorBrewer 2.0
- cascading style sheets (CSS) 65, 70, 71–72
- CCC 5, 12
- ChatGPT 73, 74, 127–129, 130, 165–166, 166, 200
- ChatGPTQualDeuter 164–165, 165
- ChatGPTQualProtan 164–165, 165
- Chevreur, Michel Eugène 16
 - color wheel 16
- chroma 57–59
- chromatic colors 57
- chromaticity 30–31
- CIE XYZ color space 45–49
- CMYK *see* Cyan, Magenta, Yellow, and Key Black
- Color and Light: A Guide for the Realist Painter* (Gurney) 189
- Color: A Photographer's Guide to Directing the Eye* (Foster) 189
- color appearance model (CAM) 52–53, 192
- Color Blindness Simulator (Coblis) 32, 33, 34, 34
- ColorBrewer 2.0 147–149
 - “3-class Set2” qualitative color scheme 152
 - with only two variables 152
 - photocopy safe and printer-friendly options 151
 - selecting qualitative color scheme 150–151
- color capture 74–75
- color constancy 28
- color cords 90
- color deficiencies 31–34, 144, 190
- color detection
 - color hex codes or RGB numbers 167
 - identify fresh color schemes, everyday objects 166–172
- color gamut 40–41, 41, 42, 191, 192
- color harmony 56, 90–91, 195
 - analogous 91, 93
 - analogous complementary 95–98
 - Bauhaus contributions to 112–114
 - color wheels *see* color wheels
 - complementary 93
 - diad complementary 101–103
 - double complementary 98–99
 - gamut masking for 105–106
 - monochromatic 91–92
 - split complementary 95
 - tetrad complementary 100–101
 - triad complementary 103–105
- color hex codes 70–71, 73–74
- colorimetry 43–44, 191
 - concepts of 192
- colorizing data visualization 162–166, 199
 - applying five-stage process 167–171
 - applying generative AI (ChatGPT), five-element data set 165–166

- colorizing data visualization (*Cont.*)
 - ChatGPT, qualitative color scheme suggestions 163–164
 - ChatGPTQualDeuter and ChatGPTQualProtran suggestions, Adobe Color 164–165
- colorizing visualization
 - data 162–166
 - tropical storm animation 180–186
- color mixing challenges 9
 - blue and yellow mix 11–12
 - red and blue become secondary 9–10
- color models
 - color theory application 16–18
 - Cyan, Magenta, Yellow, and Key Black 4, 7–8
 - perceptual limitations, human vision 18
 - Red, Green, and Blue 4, 5, 5–7
 - Red, Yellow, and Blue “painters” 4, 8–9
- color monochromacy 33–34
- Color Palette Software (COPASO) 139–141
- Color picker tool 66–67
- Color Scheme Designer 141–143
 - left panel color wheel and color selection functions 143, 143
 - right panel display and vision simulation functions 144, 144
 - selecting and implementing square-tetrad color scheme 145
- color scheme designs 145–146
 - Viz Palette 145–146
- color selection functions 143
- color spaces 41–42
 - hue, saturation, and lightness *see* hue, saturation, and lightness (HSL)
 - hue, saturation, and value *see* hue, saturation, and value (HSV)
 - lightness, chroma, and hue (LCH) 67–70
 - RGB 43
- color themes 134
- color theory 188, 195
 - application 16–18, 77–78
 - to digital media and visualization 2
 - history 12–16
 - opponent 23–24
- color tree 53
- color vision
 - deficiencies 31, 35
 - human vision 21–22
 - luminosity 29–30
 - opponent color theory 23–24
 - rainbow color map 35–38
 - simulating and designing 34–35
 - trichromatic 22, 22
 - visible light spectrum 20–21
- color wheel of complementary colors (Goethe) 188
- color wheels 83
 - Cyan, Magenta, Yellow, and Key Black printers 84–85
 - hues 87
 - Red, Green, and Blue display model 84
 - Red, Yellow, and Blue 85–86
 - shade 89
 - tints 87–89
 - tones 89
 - warm and cool colors on 89–90
- COLOURlovers’ community 138–141
- COLOURlovers’ COPASO 198
 - capturing color palette from image with 140–141
 - creating color palette with 139–140
- complementary colors 56
- complementary harmony 93, 94, 95
- compound color wheel 13
- cone cells 6
- cool colors, on color wheels 89–90
- COPASO *see* Color Palette Software
- correlation, biological data 172–180
 - color scheme solution designing 173–180
 - identifying patterns associated 180
- Creating Visual Depth, and Conveying Emotion* (Foster) 189
- CSS *see* cascading style sheets
- Cyan, Magenta, Yellow, and Key Black (CMYK) 4, 7–8, 84–85, 132, 188
 - color wheel 85
 - printing 77
 - RGB and RYB 86–87
- Cyan analogous color harmony 121
- Cyan analogous theme 134, 135
- data analytics 1
- Data Color Picker 158–160, 159
 - creating diverging color scheme with 158–160, 160
 - creating single-hue sequential color scheme with 158, 159
- data color schemes
 - diverging schemes 118, 119–122
 - generative artificially intelligent (AI) systems 126–129
 - history 117–118
 - qualitative schemes 118, 122–124
 - sequential color scheme, Adobe Firefly 126–127
 - sequential schemes 118–119
 - types of 118
- data visualization 1, 3
- deuteranopia 32, 35, 36, 190
- diad complementary harmony 101–103
- diad harmony 103, 104
- diverging schemes 118, 119–122
 - and complementary color harmonies 120

not complementary color harmonies 122
 portfolio building, ChatGPT 127–129
 double complementary harmony 98–99, 99
 Field, George 109–110, 110
 Gamut masking, for color harmony 105–106
 Gamut Mask Tool 106, 106, 195
 generative artificially intelligent (AI) systems
 126–129
 Green-Blue sequential color scheme 121
 Green cone color deficiency 31–33
 simulation 32
 Green-Red (deuteranopia) deficiency 32, 35, 190
 HCL Wizard 152–154, 154
 HCL Wizard Palette Creator Tool
 creating example 155–156, 156–158
 exploring 154, 155
 Helmholtz, Herman von 23
 Hering, Ewald 23
 opponent color theory concept 23
 hex triplets 70–71
 HSL *see* hue, saturation, and lightness
 HSV *see* hue, saturation, and value
 HTML *see* Hypertext Markup Language
 hue 55–56, 57, 67–70, 195
 on color wheels 87
 defined 62
 hue, chroma, and luminance (HCL)
 geometry 68
 and lightness 67–68
 perceptual uniformity and color deficiency
 68–69
 hue, saturation, and lightness (HSL)
 color selection application using 66–67
 color spaces 193
 comparison of 64–66
 geometry of 62–64
 historical development of 60–61
 mixing RGB lights 60
 hue, saturation, and value (HSV) 87
 color selection application using 66–67
 color spaces 193
 comparison of 64–66
 geometry of 62–64
 historical development of 60–61
 mixing RGB lights 60
 human vision 21–22
 Hunter Lab color space 52
 hurricane animation sequence, color scheme for 181–186
 Hypertext Markup Language (HTML) 70, 71–72
 inkjet printer's color space 191–192
Interaction of Color (Albers) 114, 195

International Commission on Illumination (CIE),
 color space
 LAB 50–52
 LUV 49–50
 x-y chromaticity diagram 45–49
 isosurface 181–182
 Itten, Johannes 113
 Joint Photographic Experts Group (JPEG) 34
 Josef Albers app, interaction of color by 114
 JPEG *see* Joint Photographic Experts Group
 Kandinsky, Wassily 112
 Klee, Paul 112
 left panel color wheel 143, 143
 lightness, chroma, and hue (LCH) 67–70
 lightness, defined 64
 Line of Purples 47, 48
 long, medium, and short (LMS) color space 26
 luminosity 29–30, 30
 Magenta 14, 29, 29, 37
 Magenta-Green complementary color harmony 122
 Maxwell, James Clerk 7
 Red, Green, and Blue (RGB) color model 7
 metamerism 27
 misleading color 53, 192
 mobile color tools 132
 mobile phone's color space 191
 Mondrian, Piet 17
 paintings 17
 monochromacy color deficiency simulation 34
 monochromatic harmony 91–92, 119
 multi-hue sequential sequences 119
 Munsell color system 83, 192
 evolution of 53–55, 54
 geometry of 55–59
 hue 55–56, 57
 scales and digital media 59–60
 neutral colors 57
 Newtonian color map *see* rainbow color map
 Oklab 70
 Oklch 70
 online tools, overview of 132
 opponent color theory 23–24, 190
 Orange Squared color scheme 146
 Paletton.com, Color Scheme Designer 141–145,
 142, 198
 Pantone color guide 193

- Pantone color-matching system (PMS) 42, 75, 193
 - evolution of 76–77
 - supporting CMYK printing process 77
- Pantone Connect app
 - applying color theory concepts using 77–78
 - color harmony with 78
- photocopy safe 151
- photoreceptors 6
 - cells 21, 24, 31
- Pink-Yellow-Green diverging color scheme 121, 122
- PMS *see* Pantone color-matching system
- Prang, Louis, color wheel instruction writings 111–112
- Prang color wheel 111–112
- primary color wheel, for RGB 107
- printer friendly options 151
- prismatic color wheel 13
 - for RGB 107
- ProPhoto RGB 43
- protanopia 35, 36, 190
- qualitative schemes 118, 122–124
 - 5-class qualitative schemes, color deficiency issues 124
 - 6-step qualitative color scheme 123
 - and square color harmonies 124
 - and triad color harmonies 124
- rainbow color maps 35–38, 36, 37
 - use of 191
- rectangular harmony 100
- Red, Green, and Blue (RGB) 4, 5, 5–7, 132, 188
 - color spaces, in digital media and visualization 43
 - display color wheel 84, 84, 192
- Red, Yellow, and Blue (RYB) 4, 8–9, 85–86, 188
- Red based tetrad 140
- Red cone color deficiency 31
 - simulation 32
- Red-Green channel 23
- Red-Green (protanopia) deficiency 35, 190
- reference color 43
- retina 21–22, 24–28, 31
- Revised Cyan Analogous color scheme 134, 135
- RGB *see* Red, Green, and Blue
- RGB color spaces, gamut map 44
- right panel display 144, 144
- rod monochromacy 33–34
- Rood, Ogden N. 110–111, 111
- Runge, Philipp Otto 108, 109
- RYB *see* Red, Yellow, and Blue
- saturation 63
 - defined 63
- Scalable Vector Graphics (SVG) 70, 71–72
 - sequential schemes 118–119
 - multi-hue sequential sequences and analogous color harmonies 119
 - single-hue sequential sequences and monochromatic color harmonies 119
 - shades 195
 - on color wheels 89
 - single-hue sequential sequences 119
 - Special Interest Group on Graphics Conference (SIGGRAPH) 61
 - spectral locus 47
 - split complementary harmony 95, 96
 - Spring Garden color scheme 135–136, 140–141
 - square harmony 101
 - square-tetrad color scheme, selecting and implementing 145
 - standard (colorimetric) observer 45
 - SVG *see* Scalable Vector Graphics
 - terrain function 149
 - tetrad complementary harmony 100–101
 - tetrad–rectangular harmony 100, 100–101, 101
 - tetrad–square harmony 101, 102
 - text-based generative artificially intelligent (generative AI) systems 73–74
 - theory of trichromatic color vision (Young and Helmholtz) 190
 - three-color printing process 7
 - tints 195
 - on color wheels 87–89, 88
 - tones 195
 - on color wheels 89, 89
 - treemap visualization 16–18
 - triad complementary harmony 103–105
 - triad harmony 104, 105, 124
 - trichromacy 24–28
 - trichromatic color vision 22
 - tristimulus values 43, 45, 46
 - tritanopia 35, 36, 190
 - tropical storm animation 180–186
 - climate change impact 180–186
 - hurricane animation sequence 181–186
 - UCS *see* uniform chromaticity scale
 - uniform chromaticity scale (UCS) 49
 - value
 - defined 63–64
 - scale 57
 - Vanitas PBY color scheme 170, 171
 - Vanitas RGY color scheme 170, 171
 - visible light spectrum 20, 20–22
 - vision simulation 145
 - functions 144

W3C *see* World Wide Web Consortium

warm colors 89–90

web colors 70

 HTML, CSS, and SVG 71–72

 mobile and online apps 74–75

web safe colors 72–73

World Wide Web Consortium (W3C) 70, 71

 color specifications 193

Yellow-Blue channel 23

Young–Helmholtz theory, of trichromatic color
 vision 190